

Extended mind for the design of human environment

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Extended mind for the design of human environment

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Editorial: Extended mind for the design of human environment

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Editorial on the Research Topic

Extended mind for the design of human environment

When, in 1998, [Clark and Chalmers, 1998](#) proposed the extended mind hypothesis, they challenged one of the most deeply entrenched assumptions in the philosophy of mind: that cognitive processes are confined within the boundaries of the skull. Their pithy principle suggested that if an external process functions in a way that, were it carried out internally, we would have no hesitation in counting it as part of the cognitive process, then that external process is part of the cognitive process. This seemingly simple thought experiment opened a vast conceptual territory that has since been explored across cognitive science, philosophy, psychology, and, increasingly, the disciplines concerned with the design and planning of the built environment.

The idea that architecture, urban spaces, and the material infrastructure of everyday life might play a constitutive rather than merely causal role in human cognition is not, however, entirely novel. As early as the 1930s, the Austrian-American modernist architect [Neutra, 1954](#) developed an interest in physiological psychology and argued that the design of residential spaces could potentially alleviate neurotic conditions in their inhabitants. His visionary work, *Surreal Through Design* (1954), anticipated what would later become environmental psychology: the systematic study of how physical surroundings shape perception, behavior, and wellbeing. In more recent decades, scholars such as [Pullamman, 2005](#) have further advanced research at the intersection of neuroscience, embodiment, and architectural design, emphasizing that our experience of the built world is fundamentally multisensory and that materials, textures, and spatial configurations resonate with the body in ways that precede and exceed conscious deliberation.

This Research Topic was conceived to bring together contributions from architecture, neuroscience, psychology, urban planning, cognitive science, and design studies, all converging on a shared question: how does the built environment participate in, and shape, human cognitive, affective, and social processes? The Research Topic that has emerged is remarkably diverse and yet surprisingly coherent, spanning theoretical frameworks, empirical investigations, computational models, and design proposals across four continents. In what follows, we offer a reading of the twenty-one contributions that compose this Research Topic, organizing them into an overarching

conceptual architecture that reflects the multiple dimensions along which the extended mind paradigm intersects with the design of human environments.

A first cluster of contributions addresses the theoretical and conceptual foundations linking extended and embodied cognition to the built environment. *Candelero et al.* provide a systematic historical and philosophical mapping of the relationship between extended mind theories and urban planning, tracing three successive waves (functionalism, social externalism, and radical enactivism) and their corresponding implications for reorienting urban planning approaches. By conceptualizing the city as a distributed socio-cognitive architecture, they argue that participatory design, environmental affordances, and enactive engagement with the urban space are not optional add-ons but intrinsic requirements of cognitively informed planning. This contribution provides a theoretical scaffolding for the entire Research Topic.

Vale extends this conceptual terrain by introducing the notion of the Behavioral City, a framework that integrates behavioral urbanism and behavioral public policy into a unified approach to city design. Drawing on the traditions of bounded rationality and enactive problem-solving, he argues that built environments function as systems of social affordances through which embodied agents engage in reciprocal feedback loops. His concept of enactive analyzing, that focuses on how urban spaces actively shape behavior through their material and spatial properties rather than through abstract informational cues, offers a powerful bridge between cognitive science and urban policy.

Grusani et al. directly engage with the concept of the extended mind of public space, proposing a theoretical framework in which squares, parks, and gathering places function as laboratories for human experience and wellbeing. Their identification of six design paradigms—ritual-based, body-based, sensory-based, atmospheric-based, performance-based, and intelligent/augmented-based—provides a systematic taxonomy that connects spatial design features to different modalities of cognitive and experiential extension. This contribution lays foundational groundwork for a design-oriented testing of the extended mind hypothesis.

Chamlaibous et al. extend this theoretical framing in a complementary direction by focusing on situated affectivity and the orchestration of brain-body-environment rhythms. Their perspective article challenges the computational metaphor of the brain by proposing that cognition emerges through the resonance of brain-body systems that become attuned to environmental rhythms. Drawing on evidence from neural entrainment research, they argue that the built environment's temporal and rhythmic properties such as its patterns of light, sound, movement, and spatial recurrence, are not merely background conditions for cognition but active participants in the orchestration of perceptual, affective, and cognitive states.

Ranfhiricos et al. contribute an innovative empirical operationalization of an emerging concept in urban design: lovelability. Moving beyond the more established notion of livability, which focuses on infrastructure, functionality, and services, they investigate the emotional bonds that city dwellers form with psycho-spatial aspects of urban environments. Through on-site surveys administered in two creative cultural third places (Museums Quarter Haupthof in Vienna and Plaza de Joan

Goyanes in Barcelona), they argue that lovelability is quantifiable and that its dimensions involve a complex interplay of psychological and spatial factors, providing empirical evidence that affective resonance between persons and places is amenable to systematic investigation and design intervention.

A second cluster of contributions explores how specific design features and environmental conditions shape human perception, neurophysiology, and behavior. *Mamhar and Karickhanezi* present a neurourbanism pilot study conducted in Calicut, Kerala, using mobile EEG technology to measure how diverse urban settings varying in street enclosure, natural features, and activity levels, influence neurophysiological states including excitement, engagement, interest, relaxation, and stress. As the first application of mobile EEG in a South Indian urban context, their work provides direct neurophysiological evidence that urban design shapes cognitive and affective experiences in real time.

He et al. address a complementary dimension of the environment-mind interface through their multi-objective optimization study of residential building glass in Chinese summer-hot and winter-cold regions. By employing genetic algorithms to simultaneously optimize energy consumption, carbon emissions, and indoor health performance parameters, they show how the material properties of the building envelope such as light transmittance, thermal transfer, and solar heat gain, have measurable consequences for occupant health and wellbeing, showing how the physical mediation of environmental stimuli through architectural elements affects the biological and cognitive substratum of human experience.

Rama et al. offer a culturally rich counterpoint through their study of vernacular facades in the Bhal region of India. Using visual ethnography and grounded theory techniques, they identify eight thematic levels of human-nature connections fostered by the spatio-artistic features of traditional half-timber dwelling entrances. Their findings reframe vernacular architecture as an exemplar of relational design, i.e., a form of built environment that has long facilitated the kind of cognitive and affective extension that the extended mind hypothesis theorizes, through the intimate interweaving of spatial, artistic, and ecological elements.

Alfaro et al. examine the adaptive reuse of industrial heritage buildings through a case study of the Erbil Silo in Kurdistan-Iraq, proposing its transformation into a hotel. Their qualitative analysis of design strategies for spatial transformation demonstrates how the cognitive and cultural memory embedded in industrial structures can be preserved and reactivated through adaptive reuse, illustrating that built heritage functions as a form of collective extended memory: a material repository of cultural identity that mediates between past experience and contemporary use.

A third cluster brings computational, technological, and methodological innovation to the interface between cognition and the built environment. *Gangotri and Lucifora* present BEACON (Built Environment Architecture Cognitive Ontology Network), a comprehensive multi-layer ontological framework that integrates physical, experiential, social, normative, behavioral, cognitive, and neural analytical dimensions. Applied in a comparative analysis of Pachim's central square in Sicily across historical and contemporary configurations, BEACON demonstrates how AI-assisted methods can extract tacit knowledge from built environments, offering a structured

methodology for making the extended mind legible to both researchers and practitioners.

Ulrich *et al.* (2024) present a hybrid workflow for predictive pedestrian movement modelling that integrates an agent-based model with a network model. Their approach provides urban planners with a comprehensive tool for simulating how spatial configurations shape pedestrian behavior at both micro and macro scales. By predicting how people will navigate urban environments before they are built, this contribution operationalizes a key implication of the extended mind thesis: that spatial design does not merely accommodate movement but actively constitutes the cognitive-motor patterns through which inhabitants engage with their surroundings.

Bayramov *et al.* (2024) contribute a quantitative assessment of urban surface deformation risks in Almaty, Kazakhstan, using multitemporal satellite remote sensing. Primarily a geophysical study, their work reveals how subsurface geological dynamics like tectonic movements and ground deformations invisible to everyday perception create material risks for the built environment that ultimately constrain and shape the conditions of urban habitation. This contribution extends the scope of the extended mind framework to include the geological substrate upon which cognitive environments are constructed.

A fourth cluster addresses the socioeconomic, behavioral, and public health dimensions of the human-environment relationship, bringing the extended mind paradigm into the domain of urban systems and population-level outcomes. Ouyang and Bai (2024) investigate how social media facilitates public participation in Chinese urban planning through the lens of place attachment, using the Guangzhou banyan tree incident as a case study. Their analysis demonstrates that the emotional connections residents form with elements of their built environment, i.e., what the extended mind framework would characterize as affective scaffolding, can mobilize collective action and reshape urban governance, showing how cognitive-environmental coupling operates at the political and institutional scale.

Friston *et al.* (2023) examine environmental predictors of active commuting to school among German adolescents through a mixed-methods approach combining parental and adolescent perspectives. Their findings reveal how the built environment's physical infrastructure of sidewalks, cycling paths, street lighting, and traffic density shapes the decision-making processes through which families negotiate transport mode choices beyond mere mobility patterns. This contribution shows that the extended mind operates developmentally, as the spatial affordances of the built environment structure the cognitive habits and embodied routines that form during adolescence.

Chen and Fan investigate how urban amenity, understood as the subjective attractiveness of urban environments, affects the willingness of college-educated youth to remain in Chinese first-tier cities. Their development of an urban amenity scale based on subjective evaluation captures how the cognitive and affective qualities of urban environments influence major life decisions, highlighting that the extended mind operates not only at the level of individual perception but also through the aggregate socioeconomic dynamics that shape urban populations.

Fang *et al.* focus on the gendered dimensions of urban experience through their study of female-friendly residential

facilities in Yangpu District, Shanghai. Drawing on 923 survey responses and structural equation modeling, they show that the built environment of community facilities significantly influences perceptions of female-friendliness and residential satisfaction. This contribution stresses the point that the extended mind is not a gender-neutral abstraction: the ways in which environments scaffold cognition, affect, and social interaction are shaped by embodied social identities and differential patterns of spatial use.

Liu *et al.* contribute a methodologically sophisticated coupled model linking infectious disease hazard and urban vulnerability across eighteen cities in Sichuan Province, China. Their hazard-vulnerability risk coupling model reveals that economic, spatial, social, and environmental factors display pronounced interaction effects and spatial heterogeneity in shaping public health risk, underscoring that urban environments are active systems whose structural properties cascade through population-level health outcomes.

Zhao *et al.* examine the spatio-temporal coupling between carbon emissions from urban land use and ecosystem service values at the municipal scale across China. Their analysis contributes to the extended mind framework by demonstrating that the ecological infrastructure of urban environments (green spaces, waterways, and land use patterns) constitutes a fundamental dimension of the experiential environment within which human cognitive and affective lives unfold.

Jędruszek-Kozłowska *et al.* provide an instructive contribution through their study of skin cancer prevention behaviors in the Polish population during the COVID-19 pandemic. Their findings illuminate a critical dimension of the human-environment interface: the ways in which public health crises restructure the relationship between individuals and their physical surroundings, altering patterns of outdoor exposure, preventive behavior, and health risk perception. The pandemic fundamentally reconfigured the cognitive ecology of built and open environments, revealing the normally invisible scaffolding that environments provide for health-related cognition and behavior.

Several cross-cutting themes emerge from this Research Topic that deserve emphasis. First of all, the remarkable methodological pluralism on display, spanning mobile EEG, structural equation modeling, visual ethnography, ontological frameworks, genetic algorithms, agent-based simulations, satellite remote sensing, and discourse analysis, demonstrates that the extended mind paradigm is not tied to any single disciplinary model but can be productively investigated through radically diverse approaches. Moreover, the geographic breadth of the Research Topic encompassing India, China, Austria, Spain, Italy, Cyprus, Germany, Poland, Kazakhstan, and Iraq, reveals that the cognitive entanglement of mind and built environment is a universal phenomenon that nonetheless takes culturally specific forms, from the biophilic thresholds of Gujarati vernacular architecture to the place attachment politics of Guangzhou's banyan trees. Finally, the Research Topic operates across multiple scales of analysis, from the neural oscillations measured in individual brains to the population-level dynamics of urban migration and public health risk, suggesting that the extended mind paradigm offers a genuinely multi-scalar framework for understanding how built environments participate in human cognitive life.

Taken together, these twenty-one contributions demonstrate that the extended mind hypothesis, when applied to the built environment, is not merely a philosophical proposition but a productive research program with empirical traction across multiple disciplines and scales of analysis. What emerges from this Research Topic is a vision of design as cognitive stewardship: the deliberate shaping of environments that support, extend, and enrich the mental lives of their inhabitants. This vision demands a genuinely transdisciplinary approach that integrates the insights of neuroscience, psychology, architecture, urban planning, economics, public health, and computational science. As urbanization accelerates and the challenges of sustainable, equitable, and health-promoting design become ever more urgent, the framework developed across these contributions offers both a conceptual compass and a methodological toolkit for navigating the complex entanglement of mind, body, and built world.

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References

- Bayraktar, E., Isler, N., Sazdovitch, J., Tolosanni, A., Smith, J., and Ghent, E. (2024). Quantitative prediction of office worker behavioral needs from historical and sensory activities using orthogonal networks: initial results using a case study of Albany city and its surroundings in Kazakhstan. *Front. Built Environ.* 10, 1102401. doi:10.3389/fbu.2024.1102401
- Cash, A., and Chomsky, D. J. (1998). The extended mind. *Analysis* 58, 7–10. doi:10.1093/analysis/58.1.7
- Norman, R. J. (1994). *Sensory design*. New York, NY: Oxford University Press.
- Guoqing, Y., and Bei, X. (2024). Social media for public participation in urban planning in China based on place WhatsApp – A case of the gongzhuan hantou tea stadium. *Front. Built Environ.* 10, 1102378. doi:10.3389/fbu.2024.1102378
- Polansky, J. (2020). *The rise of the data architecture and the sense*. Chelmsford: John Wiley and Sons.
- Younis, C., Akers, L., Beck, P., Doherty, K., Ramminger, D., Jermolov, Y., et al. (2022). Parental and adolescents' perspectives on organizational predictors of active commuting to school – findings from the ARSVD mixed-methods study. *Front. Built Environ.* 10, 1494837. doi:10.3389/fbu.2024.1494837
- ElBach, A., Hungen, P., Sarrasidis, I., Black, A., Jeong, K., Tordani, Y., et al. (2023). A hybrid workflow connecting a network and an agent-based model for pedestrian pedestrian movement modeling. *Front. Built Environ.* 10, 1447377. doi:10.3389/fbu.2024.1447377

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Optimal site selection strategies for urban parks green spaces under the joint perspective of spatial equity and social equity

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Urban park green spaces (UPGS) are a crucial element of social public resources closely related to the health and well-being of urban residents, and issues of equity have always been a focal point of concern. This study takes the downtown area of Nanchang as an example and uses more accurate point of interest (POI) and area of interest (AOI) data as analysis sources. The improved Gaussian two-step floating catchment area (G2SFCA) and spatial autocorrelation models are then used to assess the spatial and social equity in the study area, and the results of the two assessments were coupled to determine the optimization objective using the community as the smallest unit. Finally, the assessment results are combined with the k-means algorithm and particle swarm algorithm (PSO) to propose practical optimization strategies with the objectives of minimum walking distance and maximum fairness. The results indicate (1) There are significant differences in UPGS accessibility among residents with different walking distances, with the more densely populated Old Town and Honggu Tan areas having lower average accessibility and being the main areas of hidden blindness. While the fringe areas in the northern and south-western parts of the city are the main areas of visible blindness. (2) Overall, the UPGS accessibility in Nanchang City exhibits a spatial pattern of decreasing from the east, south, and west to the center. Nanchang City is in transition towards improving spatial and social equity while achieving basic regional equity. (3) There is a spatial positive correlation between socioeconomic level and UPGS accessibility, reflecting certain social inequity. (4) Based on the above research results, the UPGS layout optimization scheme was proposed. 29 new UPGS locations and regions were identified, and the overall accessibility was improved by 2.76. The research methodology and framework can be used as a tool to identify the underserved areas of UPGS and optimize the spatial and social equity of UPGS, which is in line with the current trend of urban development in the world and provides a scientific basis for urban infrastructure planning and spatial resource allocation.

KEYWORDS

urban park green spaces, park quality, Gaussian two-step floating catchment area, accessibility, spatial equity, social equity

1 Introduction

Urban densification has emerged as a prevailing global development trend (1), wherein the concentration of buildings and populations exacerbates the conflict between the provision of public resources and population demands (2). Particularly in China, ensuring an equitable and just allocation of social public resources has become a pivotal focus in formulating urban

development plans by the Chinese government (3). Urban park green spaces (UPGS), as the fundamental building block of social public resources, carry many benefits for urban ecology, economy, and society (3–6). They provide urban residents with places for daily activities, are important in enhancing the health and well-being of urban residents, and are regarded as a key factor in ensuring their physical health and well-being (7). However, in high-density urban environments, the mismatch between social supply and demand constrains the fairness of residents' enjoyment of UPGS resources and undermines their right to enjoy social public resources equally (8). Therefore, it is of great significance to study the supply-demand relationship of UPGS and optimize the spatial layout of UPGS to improve the well-being of residents, promote the fairness of supply-demand, and the sustainable development of the city.

The study of UPGS equity has its origins in the "environmental equity" movement in the United States (9). Up to now in development, research on UPGS equity measures has undergone three stages: territorial equality, spatial fairness, and social fairness (10). Among these stages, territorial equality emphasizes the equitable distribution of UPGS quantity and area in the macro-geographical space (11). Spatial equity introduces the important indicator of accessibility, which reflects the interrelationship between the supply of UPGS and the demand of the population, intending to seek a balance between the two (12). Social fairness primarily addresses disparities in UPGS service levels among different types of residents, shifting focus from objects to individuals (13). Overall, UPGS equity research has evolved from the initial geographical parity to the use of accessibility modeling to explore spatial equity; to social equity that simultaneously considers spatial layout, group differences, and human needs (14). At this stage, research has focused on the relationship between accessibility equity and resident attributes, such as the fact that racial minority communities have less access to UPGS resources and recreational programs than white communities in some racially discriminatory US cities (15) and that the poor have less access to UPGS than the rich in cities with uneven regional economic development (16, 17). In addition, statistical analyses of major cities in Germany have shown differences in access to UPGS between groups of different genders and different levels of education (18), some studies in China have also disclosed that individual physical factors can lead to greater resistance to accessing high-quality UPGS for disadvantaged groups, such as children, the older adult, and pregnant women (19, 20). Thus, it can be seen that there are large differences in accessibility equity and resident attributes under different cities, and research on UPGS equity under different cities is also necessary.

Accessibility serves as a core measure for spatial equity and social fairness, which was first introduced in 1948 as a measure of "human participation potential" (21) and has progressively evolved into a critical reference factor for UPGS planning (22). Traditional approaches to measuring UPGS accessibility include methods such as the minimum distance approach (23), buffer analysis (24), gravity modeling (25), network analysis (26), and the two-step floating catchment area (2SFCA) (27). Among them, both the minimum distance method and buffer analysis method do not consider the actual road network. The former uses Euclidean distance as a criterion to calculate the straight line distance from residents to supply points, while the latter employs a predetermined search radius to identify the number and area of public facilities within that radius or calculate the number of settlements within a certain service

radius of a public facility (28). On the other hand, although the network analysis method considers the actual road network by calculating service range at a predetermined time or distance based on supply points, it fails to account for supply-demand relationships. In contrast, the gravity model method measures spatial accessibility by summing up probabilities associated with multiple facility choices at each demand location, taking into consideration attraction, supply and demand impacts as well as spatial friction. However, this approach requires complex data, and determining resistance coefficients is challenging (29). Based on two searches centered around demand and supply points, respectively, using road networks, 2SFCA builds upon the gravity model method to determine convenience between supply and demand. It also integrates urban public facility scale, demand scale, and distance relationship between supply and demand (30). Nevertheless, this method does not consider distance attenuation but defaults to assigning an equal probability of choice for residents within the same search range (28). To solve these problems, scholars have introduced various forms of extensions into the 2SFCA model, and the main directions of the extensions include the introduction of different search radii (31), the introduction of differential traveling modes (32), and the introduction of geographic impedance decay functions (33). Enhanced 2SFCA based on 2SFCA (34), Variable 2SFCA (35) Gaussian 2SFCA (G2SFCA) (36), and so on appeared. Among them, G2SFCA, compared to the other two improved models, introduces Gaussian equations based on 2SFCA, which not only takes into account the spatial barrier between supply and demand points but also captures the phenomenon that people's willingness to travel gradually decreases with the increase of distance. Therefore, its accessibility results are closer to the real situation (36, 37). Thus, after comparing the existing accessibility measurement models, we chose G2SFCA, which considers the supply-demand equilibrium and attenuation distance, as our measurement model to be improved. However, previous studies on improving UPGS reachability models and measurements have some limitations. One of the main limitations is that they mainly focus on factors such as traveling mode, distance, and environmental resistance while neglecting the impact of UPGS quality attributes on residents' probability of choice and visitor capacity. Closer and larger UPGS facilities tend to attract more visitors and provide a better experience for residents, and some UPGS infrastructures can also have limitations on visitor numbers and visitor experience (38, 39). Therefore, incorporating multidimensional UPGS quality attributes into the accessibility measurement model can help to comprehensively capture real-life accessibility resistance, as well as comprehensively reveal the rationality and fairness of UPGS layout (39). In addition, the degree of influence of UPGS quality attributes on the level of accessibility varies widely. With reference to the relevant literature, we eliminated subjective attributes such as environmental quality and landscape beauty, and finally refined the UPGS quality attributes with more objective and influential ecological service value (ESV) and recreational facility capacities (FCs), thus proposing a more accurate G2SFCA model (39).

Currently, most studies on the equity of urban parks and green spaces focus on social equity (40), assessing the reasonableness of the layout of UPGS by examining the degree of accessibility for specific groups of residents. However, no matter which attribute of residents is chosen as the research object, there is a specificity of the research

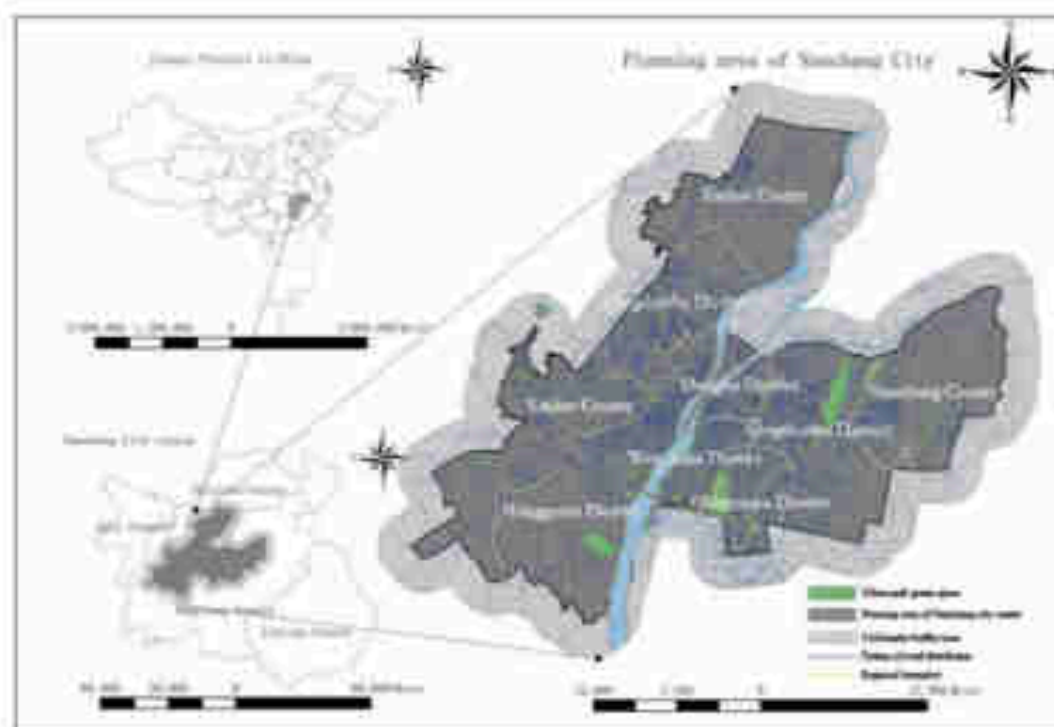


FIGURE 1
The location of Nanjing City in China, the location of Nanjing City, and the spatial distribution of UPGs

results, which limits the generality and applicability of the research conclusions to be applied in the construction of urban public space systems. In contrast, spatial equity research tends to take large-scale non-specific groups as research objects, making it difficult to accurately grasp the needs of socially disadvantaged groups. Combining these two perspectives can solve the spatial equity problems of ordinary residents with minimal computational costs while taking into account the social equity problems of special groups, providing a new direction for optimizing the equity problems in the construction of UPGs. As an effective tool for socio-economic differentiation, house prices cover all urban populations, creating opportunities for the combination of spatial and social equity. In addition, existing social equity studies have only analyzed differences in access to UPGs resources from the perspective of different demographic attributes, ignoring the social inequity situation caused by differences in economic structure. Exploring the correlation analysis between community house prices and UPGs accessibility can effectively fill this gap [36]. Particularly in China, house prices promote socioeconomic redistribution [37], leading to a homogeneous agglomeration pattern of residents with similar economic conditions in a given urban area [41–43]. On this basis, this study attempts to quantitatively assess the equity of access to urban public infrastructure services for different socio-economic groups through spatial autocorrelation analyses of house prices and accessibility in a community in Nanjing, China, and to filter out the optimization objectives under social equity. Then, the UPGs accessibility levels of all residents were stratified and the optimization objectives under spatial equity were screened. Finally, using the K-means algorithm and Particle Swarm Algorithm (PSO) with minimum walking distance and maximum fairness as the optimization principles, the two objectives

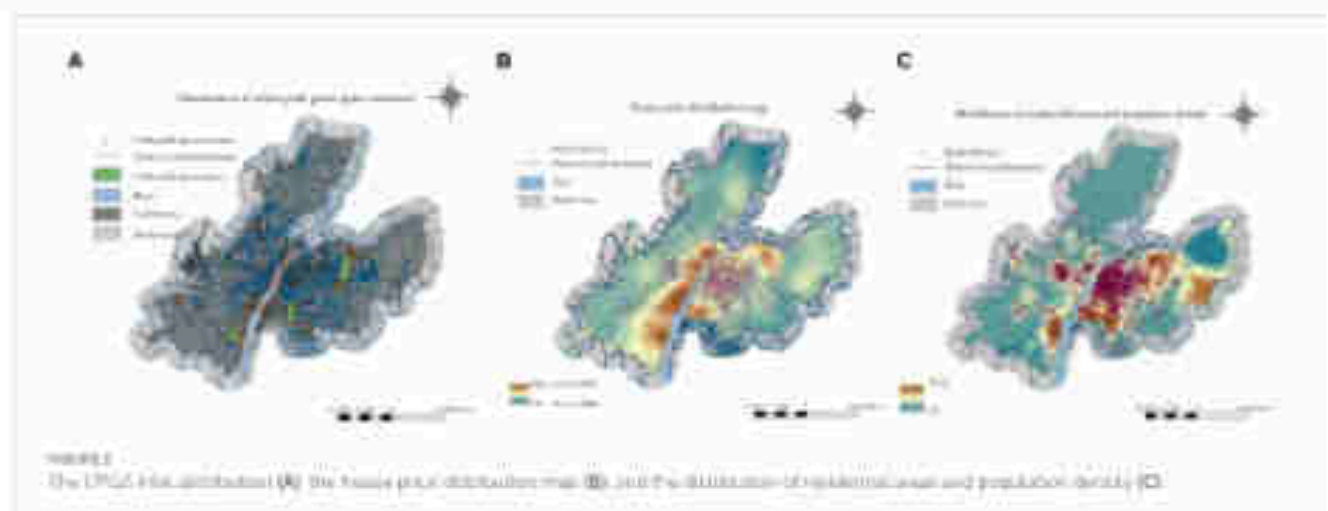
under this spatial and social fairness are used as optimization objects, and combined with the green space information in the local urban land-use plan, the location and area of parks to be built are clarified, which provide a reference for the fair distribution of high-density urban public facilities.

Taken together, the new UPGs optimization scheme proposed in this paper consists of three main parts: (1) Introducing the more objective UPGs quality attributes to improve the GISPCA model, aiming to maximize the replication of real-life UPGs accessibility instance; (2) Incorporating a social fairness perspective to determine the number of settlements to be optimized and their distribution through the coupling of spatial and social fairness; (3) Through the combination of the K-means algorithm and PSO as well as the reference of land use planning layout in the study area, new UPGs locations and areas are created for the settlements to be optimized to guide urban planning (See Figure 1).

2 Study area and research data

2.1 Study area

Earlier research cases on UPGs equity within China have focused on developed coastal cities in the Yangtze River Delta and Pearl River Delta, such as Shanghai [44, 45] and Shenzhen [46, 47]. With the increasing imbalance between the supply and demand of public service resources within each city and the advancements of regional economic integration, the research has been extended to inland cities such as Changsha [48] and Wuhan [49]. The expansion of the study cases from developed to sub-developed regions is in line with the



global trend in public resources research. This group of landlocked cities, which are economically more underdeveloped and suffer from a significant imbalance between the supply of and demand for public service resources, tends to be given greater attention, as they account for a greater number of cities globally (42).

For our case study, we chose one of China's most representative inland cities, Nanchang, the capital of Jiangxi Province. This UPGS study is directly related to the development of Nanchang's livelihoods, as Nanchang is trying to address issues such as uneven distribution of public resources and residential segregation (43), while actively developing a UPGS service that is highly relevant to the city's inhabitants, namely the "Walking Living Circle." According to statistics from the Nanchang City Planning Bureau, by the end of 2022, the per capita area of park green space in Nanchang will be 13.05 square meters, which is significantly lower than the national average of 14.87 square meters per capita. The large population base coupled with the influx of a large number of foreigners has exacerbated the conflict between supply and demand for UPGS in Nanchang (44). Geographically, it spans from east longitude 115°27' to 116°35' and from north latitude 28°10' to 29°11'. This study takes the planning blueprint presented by the Nanchang Urban Planning Bureau as the research area, with a total area of 1,000 km², including Donghu District, Xihu District, Henggutun District, Qingyuan District, Qingzhanhu District, Xinqian District, and parts of Nanchang County. Among these, Donghu District, Xihu District, and parts of Qingzhanhu District constitute the old city center of Nanchang. Additionally, considering that residents near the boundaries of the study area may use UPGS beyond the internal regions, UPGS within a 3 km buffer zone around the research area is also included for analysis purposes.

2.2 Data sources and processing

2.2.1 Park data

First, Python programming was employed to scrape the Point of Interest (POI) directory for UPGS in Nanchang City in 2023. Subsequently, the Baidu Maps open API was utilized to retrieve the Area of Interest (AOI) data for UPGS. After eliminating charged or abandoned parks and those with overlapping areas, 91 UPGS were

acquired. Following the "Nanchang Urban Green Space System Planning (Revised) (2015–2030)" and "England Natural Green Space Accessibility Guidelines – Natural Green Space Accessibility Standards," the UPGS within the research area were categorized into four groups based on area parameters: comprehensive parks ($\geq 255 \text{ hm}^2$, (21)), citywide parks (5–25 hm^2 , (45)), regional parks (2–5 hm^2 , (14)), and community parks ($< 2 \text{ hm}^2$, (3)). Referring to the existing literature on park service radii (38, 31), walking service radii for community, regional, citywide, and comprehensive UPGS were set as follows: 300 m, 1,000 m, 2,000 m, and 3,000 m, respectively. Furthermore, considering that park entrances and exits are more scientifically relevant supply points than their geographical centers (37, 39), 394 entries and exits for UPGS were identified through Google Maps recognition and on-site surveys (Figure 1A). Among these parks, due to the elongated nature of gateway-type UPGS and the absence of barriers such as walls or hedges in those areas, intersections between greenways and main roads were transformed into supply points (34).

2.2.2 Road data

Downloaded the latest road data for Nanchang City by accessing the OpenStreetMap website,⁴ and after topological checks, road network matching, data correction, and elimination import it into ArcMap 10.8 for analysis.

2.2.3 Housing and population data

The Housing POI data were collected from Anjuke, one of China's largest platforms for second-hand housing transactions.⁵ This dataset includes essential information such as the names of housing communities, latitude and longitude coordinates, construction year, community household numbers, and housing prices (price per square metre in RMB). After thorough filtering and cleaning processes, 1,024 residential points were obtained. Previous studies have demonstrated that utilizing housing unit numbers and prices as proxies for regional population distribution and residents' economic conditions can

⁴ <http://www.openstreetmap.org/>
⁵ <http://www.anjuke.com/>

TABLE 1. Weights of GS2SFCA-related indicators after improvement.

Related Indicator	Description	Weights
S	Area size of UPGS	0.226
ESV	Ecosystem service of UPGS	0.181
PCa	Public carrying capacity of UPGS (42.74) > comprehensive type (7.51) > regional type (-8.26) > community type (77.53)	0.084

significantly enhance the scientific validity and reliability of UPGS fairness measurements (55, 56). Therefore, we employed community housing prices to indicate residents' financial status (Figure 28). At the same time, the total population was estimated by multiplying the total number of households with administrative unit population data (Figure 25). The population data for administrative units were sourced from the sixth national population census at the block level in Nanchang City (Nanchang Statistical Bureau).

3 Research methodology

3.1 Improvements to GS2SFCA and accessibility measurement

The GS2SFCA method, which incorporates distance decay and supply factors, is selected for computation in this study. By integrating ESV and PCa derived from park quality into the traditional formula, a more precise GS2SFCA accessibility measurement model is developed. The specific calculation involves three sequential steps.

The first step involves calculating the contribution ratio of the comprehensive supply capacity of UPGS, which is based on the area (S), ESV, and PCa. The study shows that the fragmentation of the green landscape under urban space is an important aspect of measuring the ecological service value of the UPGS, i.e., the more fragmented the green space is, the worse the ecological service value and the social service function are (67). The landscape pattern index, as a method to quantitatively study the pattern characteristics, can effectively respond to the degree of green space fragmentation within the UPGS. Referring to related studies, three major hierarchical indexes describing patches under landscape pattern: patch spatial layout, patch shape, and patch area and density were introduced for assessing the degree of fragmentation of Greenland patches within the UPGS (68), in which the extraction of the degree of the landscape of Greenland patches was based on China's first set of 1 m-resolution nationwide land cover maps (SinelC-1) (69). Specifically, mesh size (MESH), split index (SPLIT), aggregation index (AI) as measures of patch spatial arrangement; weighted patch area size (AREA_AM), average shape index (SHAPE_MN), division index (DIVISION) as measures of patch shape; and patch density (PD), landscape patch index (LPI), and landscape shape index (LSI) as measures of patch area and density. Among them, AI, LPI, and MESH are positive indices to evaluate the quality of green space patches, PD, LSI, AREA_AM, SHAPE_MN, DIVISION and SPLIT are negative indices to evaluate green space patches there. After extracting each landscape pattern index, each index was standardized with positive and negative values, and then integrated using principal component analysis in SPSS, and finally obtained the ESV value of each UPGS. The average value of different types of UPGS: community type (77.53) > citywide type

(42.74) > comprehensive type (7.51) > regional type (-8.26) (Table 1). Furthermore, it has been well-documented that the carrying capacity of PCa, as a crucial quality attribute of UPGS, directly influences residents' willingness to visit (36, 38) as the central accommodation for PCs within UPGS, the area of hard surfaces is positively correlated with the service capacity of open spaces in most cases (80). Therefore, in this study, the scope of hard grounds in the UPGS within the study area can be extracted as an indicator for estimating the carrying capacity of PCs using the raster calculator in ArcMap 10.8.

Eventually, a judgment matrix based on the De Faut method was created through AHP (hierarchical analysis) (61) to determine the weights of park S, ESV, and PCa (Table 1). Additionally, the consistency ratio (CR) value obtained from this judgment matrix consistency test was found to be 0.08, below 0.1, and thus passed the one-time test (62).

The second step involves computing the service capacity R_i for each UPGS. A corresponding spatial influence domain is established using each entrance and exit of a UPGS as a supply point j , with j as the center and selecting d_0 as the search radius. Weights are assigned using the Gaussian equation for all resident demand points k within this domain. Subsequently, the supply-demand ratio R_i is calculated by dividing the comprehensive supply capacity of UPGS in terms of S, ESV, and PCa by the population of the weighted demand points (Eq. 1).

$$R_i = \frac{S_i w_1 + ESV_i w_2 + PCa_i w_3}{\sum_{k \in [J_i, d_0]} [G(d_{kj}, d_0) \cdot P_k]} \quad (1)$$

Where R_i is the supply-demand ratio, S_i , ESV_i , and PCa_i are the total area, ecological service value, and recreational facilities of the i th UPGS, respectively; w_1 , w_2 , and w_3 are the weights belonging to the above variables, respectively; d_0 denotes the search threshold; d_{kj} is the actual walking distance from the demand point k to the supply point j ; P_k is the total population in the role of the domain of the residents at the demand point k ; and $G(d_{kj}, d_0)$ is the distance decay function, and the calculation formula is shown in Eq. 2.

$$G(d_{kj}, d_0) = \begin{cases} \frac{1}{e^{\frac{1}{2} \left(\frac{d_{kj}}{d_0} \right)^2}} - e^{-\frac{1}{2}} & d_{kj} < d_0 \\ 1 - e^{-\frac{1}{2}} & \text{if } d_{kj} \geq d_0 \end{cases} \quad (2)$$

In the third step, the accessibility index for each demand point is computed. Taking demand point i as the search center, the supply-demand ratios R_i of all UPGSs in the d_0 spatial domain are weighted and summed by the Gaussian function, and finally, the accessibility A_i of demand point i is obtained (Eq. 3).

TABLE 2 Accessibility description statistics of various residential areas under different walking distances

Walking distance	UPGS accessibility			Number of residents with 0 accessibility	Standard deviation
	Maximum	Minimum	Mean		
500	10733	0	242884	2338	14.00181
1,000	10149	0	424910	1,819	28.89975
1,500	8842	0	2344970	157	46.26736
2,000	4491	0	5571331	24	49.61602

$$A_j = \sum_{i \in \{R_i, S_i\}} [g(d_{ij}, d_0) R_i] \quad (3)$$

3.2 Spatial autocorrelation

To identify the mismatch between the accessibility of UPGS and residents' socioeconomic levels, we utilized the GeoDa software. We employed the bivariate local Moran's index as a measure of spatial autocorrelation (63), as shown in Eq. 4.

$$I_{ij}^* = x_i^* \sum_{j=1}^n w_{ij} x_j^* \quad (4)$$

In the equation, x_i^* represents the standardized value of the independent variable x (UPGS accessibility) for region i , x_j^* represents the standardized value of the dependent variable y (community house prices) for region j , and w_{ij} is the spatial weight matrix between regions i and j . The measurement results of the bivariate local Moran's index indicate five types of spatial local associations between UPGS accessibility and residents' socioeconomic status: H-H (high accessibility, high socioeconomic level), H-L (high accessibility, low socioeconomic level), Not significant (both variables are not essential), L-H (low accessibility, high socioeconomic status), and L-L (low accessibility, low socioeconomic level).

3.3 Identification of supply blind zones

Supply blind zones refer to areas where the supply capacity of UPGS cannot adequately meet the resident's needs, and they are categorized into explicit blind zones and implicit blind zones (64). Detailed blind zones indicate regions where residents' distribution points cannot reach any UPGS within a 3,000 m walking distance. Implicit blind zones refer to areas where the service range of UPGS covers residents' movements. Still, supply imbalances occur due to high population density or insufficient UPGS capacity, resulting in residents receiving a lower level of UPGS services.

3.4 Optimisation of supply blind zones

The optimization of the supply blind zones is based on the Nanchang Land Use Master Plan and uses a combination of the k-means algorithm and the PSO algorithm. The former determines

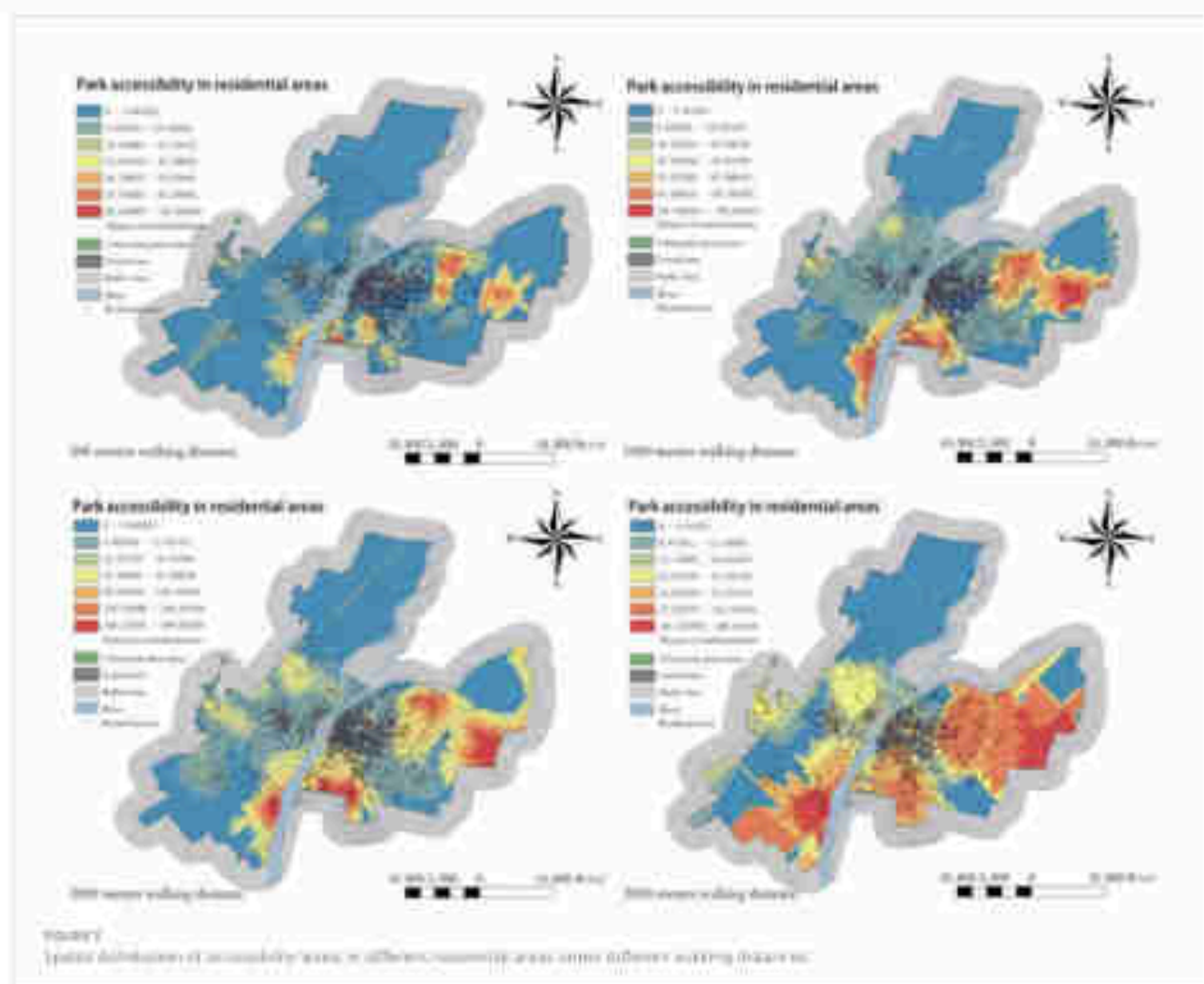
the minimum number of UPGS required for these blind zones, and the latter determines the optimal location of UPGS clusters. Among various clustering algorithms, the k-means algorithm stands out for its interpretability, simplicity, and efficiency when dealing with large-scale datasets (65). We use this algorithm to cluster the main factors affecting spatial and social equity, including spatial accessibility based on a neighborhood scale and the degree of spatial matching of socioeconomic levels, and the number of clusters is determined based on the maximum Euclidean distance of the paired samples in the two-dimensional space consisting of both. The PSO algorithm is a simulation of a simple social system such as the foraging behavior of birds and is achieved through an iterative process of Global optimisation. The algorithm has the advantages of simple implementation, high accuracy, and fast convergence (66). The PSO algorithm in this study first needs to generate a certain number of particles based on the clustering results of the K-means algorithm, with each particle representing a candidate UPGS siting scheme, and then calculate the fitness of each particle by using the sum of the products of the nearest neighbors distances between all particles as the objective function. Then, during multiple iterations, we update the velocity and position of each particle using the information of global optimum and individual optimum until a predetermined iteration limit or stopping condition is reached. The spatial location information of a certain amount of particle numbers is finally obtained as the UPGS pre-siting scheme. However, it is difficult to take into account the land use information of the city in the PSO algorithm, so the final optimization scheme is based on the principle of minimum walking distance and maximum fairness, which is refined and evaluated by the manual visual method knot and the results of the PSO algorithm with the land use information of Nanchang City.

4 Results analysis

4.1 Analysis of accessibility differences at different walking distances

In this study, an improved GISPCA method is employed to calculate the accessibility of UPGS in Nanchang City. We collected accessibility indicators of residents at different walking distances (Table 2) and examined the distribution changes in park accessibility (Figure 3). The standard deviation in the table represents the degree of dispersion of UPGS accessibility, to some extent, indicating spatial equity (39).

Results show: (1) at a walking distance of 500 meters, over two-thirds of the residents have zero accessibility to UPGS, indicating the lowest overall accessibility. Areas with higher



accessibility are concentrated in the southern and eastern edge regions. (2) When the walking distance increases to 1,000 meters, the number of residents with zero UPGS accessibility decreases significantly. However, the changes in UPGS accessibility in the old city area and the central along the Ganjiang River in Honggutan are still not pronounced. (3) With a walking distance of 2,000 meters, only one-twentieth of the residents have zero UPGS accessibility, and areas in the old city and Honggutan started to exhibit higher accessibility for residents. This suggests that the planned initial UPGS service range in Nanchang City is close to 2,000 meters, and the old city and Honggutan are two areas lacking internal UPGS supply. (4) When the walking distance extends to 3,000 meters, the number of residents with zero accessibility and the standard deviation decreases the least, while the average UPGS accessibility rises significantly. This indicates that changes in walking distance contribute the least to spatial equity at this stage. (5) In summary, UPGS accessibility for different walking distances exhibits a similar spatial pattern. The northern and southwestern parts of the city are cold spots, representing the main areas of explicit blind spots, while the eastern and southern regions are hot spots, where UPGS supply far exceeds residents' demand. Increasing residents' walking distance results in the spread of UPGS accessibility distribution from the periphery to the central

area, indicating that increasing walking distance enhances UPGS accessibility. Accessibility is positively correlated with walking distance and the number of UPGS. The old city area and Honggutan, with the highest population density, require most residents to walk more than 2,000 meters to access UPGS. This indicates a severe supply-demand imbalance in these two regions and serves as the main area of implicit blind spots. A walking distance of 2,000 meters provides the most significant improvement in spatial equity and can inform the determination of the radiation radius for additional UPGS at a later stage.

4.2 Overall accessibility disparity analysis

To visually represent the spatial distribution of overall accessibility in settlements, all UPGS accessibility data was overlaid using ArcMap 10.6 and divided into intervals using the geometric interval method to generate the UPGS comprehensive accessibility distribution layer (Figure 6) and hierarchical statistical chart (Figure 7), with settlements as units. In terms of geographic distribution, it can be found that the lowest accessibility settlements are mainly distributed in the fringe areas of settlement clusters, such as the northern part of Qingchunli District and the southern

Overall accessibility distribution of all residential areas



FIGURE 4

Overall accessibility distribution of all residential areas

Comprehensive accessibility grading statistics of UPGS within the study area

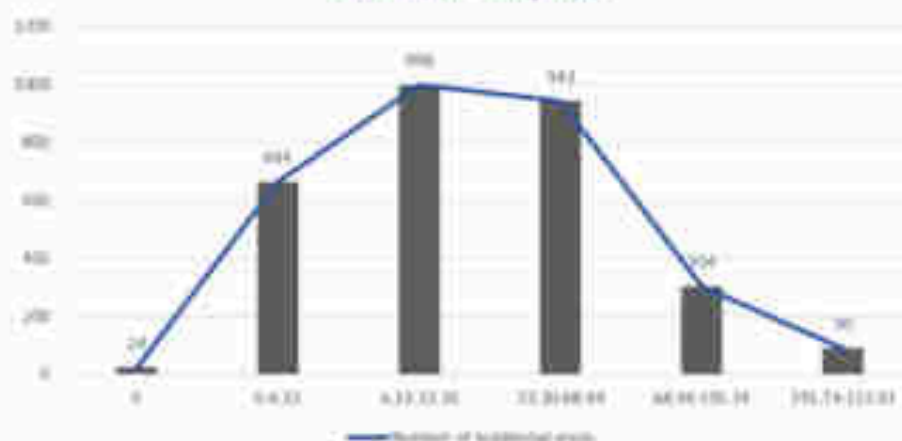


FIGURE 5

Comprehensive accessibility grading statistics of UPGS within the study area

part of Honggutan District). At the same time, the lower and medium accessibility settlements are mainly clustered in the old urban area and the opposite bank of Honggutan District. The possible reason for this is that residents on the edge of urban expansion have difficulties in having their needs for urban public infrastructure met by the government. The old city and Honggutan District, as the former and current development centers of Nanchang, are too densely populated, and demand exceeds supply; the population density directly affects the degree of accessibility.

In addition, the settlements with higher accessibility on the map are mainly located around large UPGS. It may be that the population size of these settlements is smaller, and the large UPGS have more extensive areas, ESV, and FCA, resulting in an overall higher level of accessibility for these settlements as a whole. Overall, the total accessibility of the UPGS in the central region of Nanchang City shows a spatial pattern of decreasing towards the main area in the east, south, and west, consistent with the distribution of the large UPGS.

As depicted in Figure 6, only 24 settlements exhibit zero accessibility, indicating that the implementation of UPGS in Nanchang City has essentially extended to all accommodations, achieving geographical parity. However, it is noteworthy that a significant majority (over 80%) of settlements fall into the categories of low, lower, and general accessibility levels. This suggests a deficiency in adequate UPGS accessibility throughout Nanchang, resulting in spatial inequality where limited residents enjoy most UPGS resources. Conversely, settlements with high and higher accessibility levels comprise merely 304 and 90, respectively, but the quality of accessibility provision is much higher than the other types. In conclusion, while achieving geographic parity through existing UPGS construction has been accomplished mainly in Nanchang City, future optimization should focus on enhancing spatial equity and social fairness.

4.3 Analysis of social equity in UPGS

The GeoDa software was utilized to investigate the spatial autocorrelation between the socioeconomic status of residents in the study area and UPGS accessibility. The binary global Moran index for their spatial coupling was 0.290, which passed the significance test at 0.01, indicating a positive overall spatial correlation (30). In other words, higher economic levels in an area corresponded to greater UPGS accessibility. Figure 7 illustrates a spatial mismatch between socioeconomic status and UPGS accessibility in Nanchang. Specifically, there were 192 high-high communities primarily concentrated in the southwest region near the river greenway, suggesting a shift in Nanchang's economic development from its old urban area towards the southwest. Additionally, there were 390 low-low communities mainly located within the senior city center and on the outskirts of settlement clusters, aligning with areas exhibiting lower accessibility; this represents a significant imbalance in social equity. Furthermore, there were 390 high-low neighborhoods predominantly reliant on high-high communities due to their access to UPGS resources enjoyed by

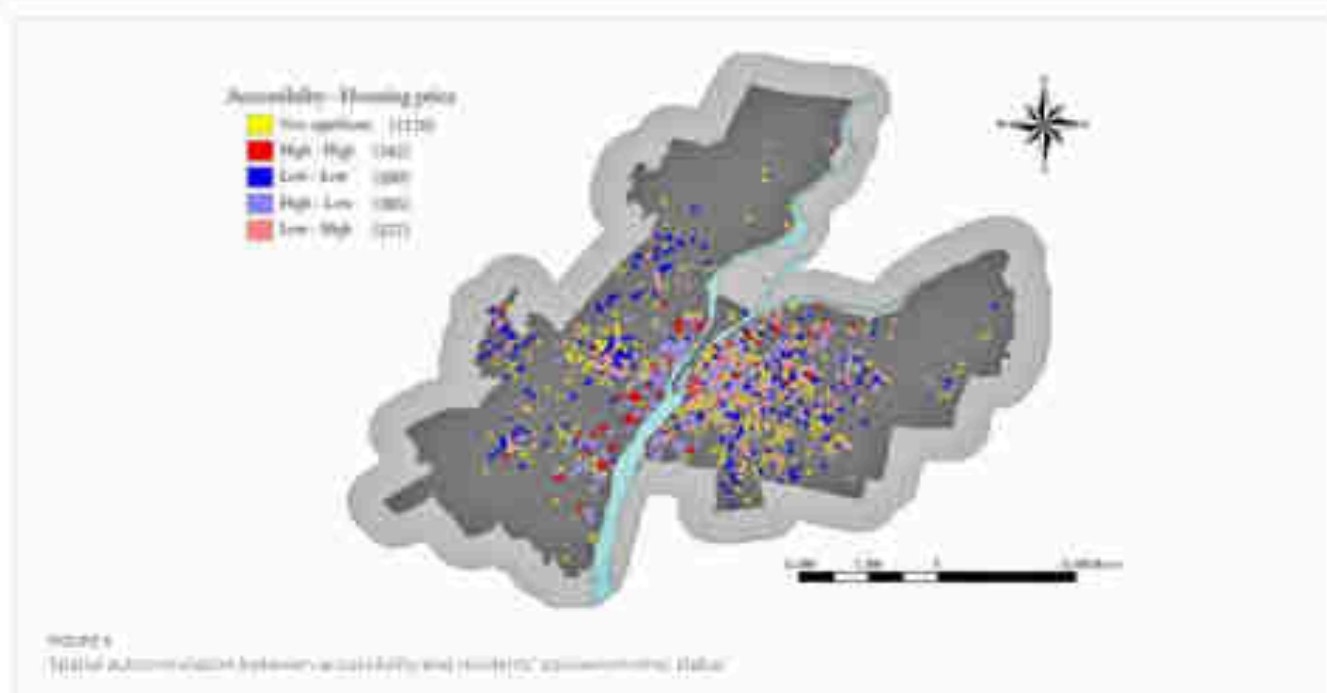
economically prosperous areas; finally, there were 177 low-high neighborhoods, which are more centrally distributed and spatially similar to the distribution of low-low communities.

5 UPGS accessibility optimization strategies

5.1 Analysis of adding UPGS quantity and site selection

To comprehensively balance the spatial equity and social equity of UPGS in Nanchang, 731 residential points that require improvement were identified by combining low accessibility residential points (0–4.333389) with low-low type communities that exhibit a socioeconomic mismatch. Subsequently, the K-means clustering algorithm in Matlab (31) was employed to determine the optimal number of UPGS through the maximum Euclidean distance in a two-dimensional space composed of accessibility and socio-economic adaptability levels of paired samples. After multiple iterations, the K-means clustering curve for optimizing UPGS in Nanchang was obtained (Figure 7A). The curve's horizontal axis represents the number of newly added UPGS, the vertical axis represents the average farthest distance from sample points to cluster centers, and the slope of the curve indicates the impact of increasing the number of cluster centers on clustering effectiveness. Due to the construction of a "20-min walking time circle" and the standard deviation of the accessibility under different walking distances, it is finally confirmed that 10 new UPGS with a radial range of 2,000 m will be added based on the original one.

The K-means algorithm addresses the issue of determining the number of new UPGS but lacks specific location information to guide practical planning. To overcome this limitation, we employed the versatile and robust PSO, known for its effectiveness in highly nonlinear and discontinuous situations (32). Therefore, the PSO in Matlab was applied to take the spatial locations of the 10 UPGS as



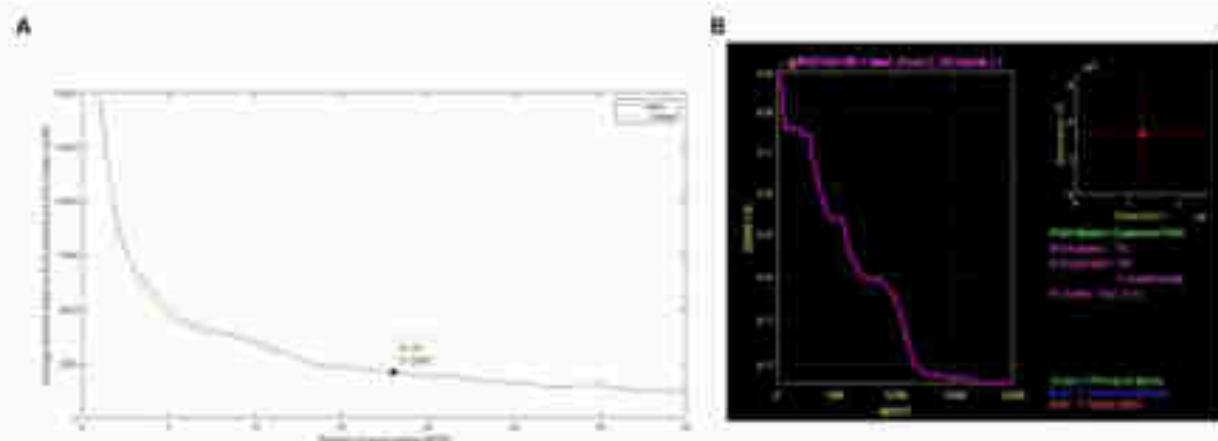


Figure 7
The UPGS quality optimization curve (A) and the radiation range of UPGS (B)

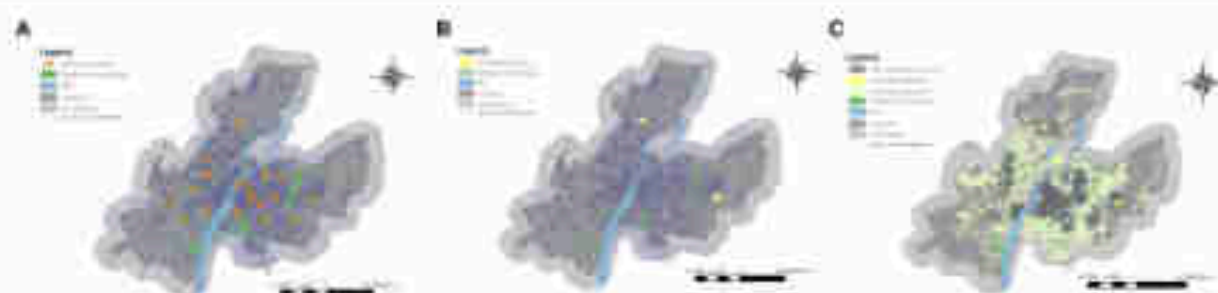


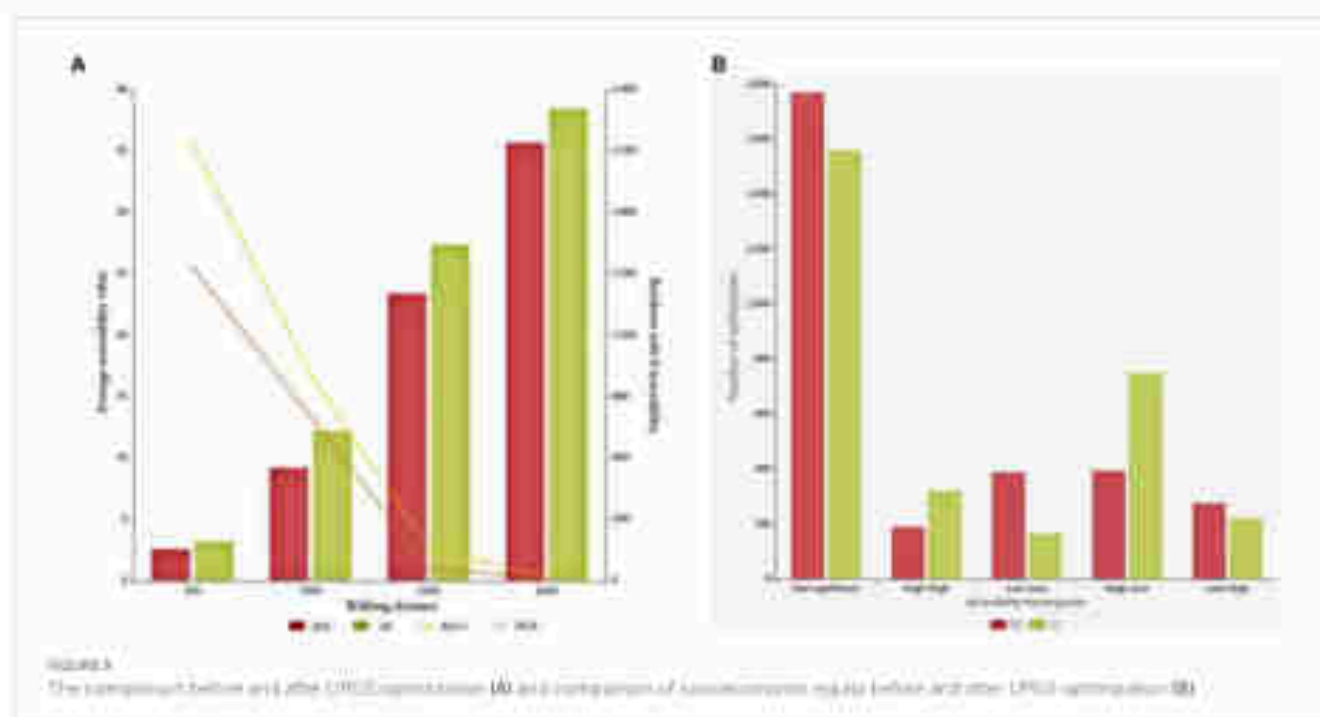
Figure 8
They added the UPGS distribution (A), the area distribution of UPGS (B), and the radiation range of UPGS (C)

the final output. The sum of the products of the population of a settlement with weak accessibility and the distance from that settlement to the nearest particle among the 18 particles was used as the objective function of optimization. The spatial information of the 18 new UPGS locations was finally obtained after nearly 2,000 iterations of the model (Figure 1A, 1A). However, the initially designated UPGS locations were all citywide parks with a radial range of 2,000 meters, which did not suit all areas of Nanchang. By integrating green space information from Nanchang's latest planning blueprint, 18 citywide UPGS locations were selected as reference centers for positioning, ultimately yielding 12 community-type UPGS, 4 regional UPGS, and 13 citywide UPGS, totaling 29 UPGS (Figure 1B). Among these, community-type UPGS primarily target areas like the old city center characterized by complex land use and land scarcity, adopting an "acupuncture" approach to disperse resources and alleviate issues of high population density and associated social inequity driven by housing prices. Regional UPGS primarily comprise small greenways, enhancing landscape continuity by incorporating the city's internal river network, and their distribution is relatively scattered. The citywide UPGS are situated in areas boasting natural beauty, convenient transportation, and a high concentration of nearby residents. They are primarily located at the periphery of residential clusters, eliminating implicit and explicit blind spots in accessibility and thus playing a crucial role

in improving overall accessibility for residents. In summary, as evident from Figure 1C, the radiation ranges of the newly added UPGS substantially overlap with the existing UPGS, highlighting that this optimization primarily focuses on addressing implicit blind spots in accessibility, with the optimization concentrating on the old urban area and the northern part of the Qingshanhu District.

5.2 Optimization results analysis

Figure 1A shows the improvement of spatial equity in Nanchang by the new UPGS, which is the optimization of accessibility to both explicit and implicit blind zones, and the overall average accessibility rises by 2.76. However, the magnitude of the improvement varies across walking distances, with the new UPGS increasing the accessibility of residents at walking distances of 1,000 m and 2,000 m the most, followed by those at walking distances of 500 m and 3,000 m. This is because the new UPGS types are mainly citywide parks with a more extensive service radius and carrying capacity than community-based UPGS. In addition, for neighborhoods with 0 accessibility, the most excellent elimination occurs within a 500 m walking distance and then decreases as the distance increases. However, there are still 11 settlements with 0 accessibility not eliminated even after increasing to 3,000 m, which may be due to the poor connectivity of the road network in these settlements, which



makes it difficult to solve the problem of accessibility provision by increasing the UPGS. For these suburban settlements with poor spatial connectivity, the focus should be on improving the service capacity of the transport road network, which will, in turn, improve the traveling efficiency and accessibility of the residents.

Figure 3B shows how the addition of UPGS has improved social equity in Nanchang City, with the most significant changes being in spatially mismatched low-low and high-low type neighbourhoods. Specifically, the number of low-low type communities decreased from 90 to 167, while the number of high-low type communities increased from 398 to 752. These findings indicate a gradual reduction in the disparity of UPGS resources resident groups enjoy across different economic levels. Moreover, it highlights the significant impact of optimizing UPGS on enhancing social equity in Nanchang.

6 Discussion

This study explores the optimization of UPGS in Nanchang under the common goal of spatial and social equity and has three primary research outcomes in the process. The first is optimizing the accessibility calculation model using more objective and easier-to-calculate ESVs and FCs. The second is that the selection of optimization objectives considers both spatial and social fairness. The third is to combine the local green space planning of Nanchang City with the K-means algorithm and particle swarm algorithm to target the minimum walking distance and maximum fairness, and to propose a more suitable local optimization scheme for UPGS.

In the allocation of public resources between multiple cities, existing improvements to UPGS accessibility measurement models primarily focus on reducing resistance to accessibility by incorporating physical and environmental factors beyond city public space stations, while neglecting the influence of UPGS's quality attributes [52, 55]. However, a few studies on accessibility models based on quality

attribute optimization often include subjective qualities, leading to significant cognitive biases in determining the importance of multiple factors [42]. In contrast, we adopt the GIPCAS method with supply-demand improvement to evaluate the accessibility and fairness of UPGS. This approach introduces more objective factors on the supply side of UPGS, such as ESV and FCs, which are more focused on expressing "bottleneck" limiting factors related to factor capacity. At the same time, quantifying these quality attributes differs from previous methods relying on expert evaluations or offline questionnaires [34, 35]. Instead, it utilizes landscape pattern indices and built surface area data as substitutes that are more transparent and easily accessible within UPGS. Therefore, this improved accessibility model ensures its potential replicability and convenience when applied in other cities. On the demand side of UPGS, the area and entrance information of the UPGS is obtained by web-crawled AHI combined with offline research to ensure the reliability of the data compared with manual depiction and purely offline survey [34, 36, 37]; the population of the community is accepted as the product of the population of the administrative unit accurate to the neighborhood, and the number of households, instead of the population estimation of the homogenized distribution with the minimum unit of the district [11], and the socioeconomic level of the residents is obtained by using web-crawled community house prices as the estimation index, which ensures the heterogeneity and accuracy of each community point compared to some social equity studies that ignore group distribution patterns [43]. In conclusion, the UPGS is statistically improved to both supply-side and demand-side measurements and data. However, in selecting optimization objectives, previous studies primarily focused on accessibility under spatial equity or accessibility under social equity, lacking a comprehensive consideration of both [23, 77]. This study used 3,024 residential points as the foundational unit of data, overlaying both objectives for optimization, aiming to minimize computational costs while considering spatial fairness and social equity. Furthermore, this overlay optimization approach is not only applicable in the socio-economic perspectives investigated in this

experiment but also extendable to other demographic groups with large population bases, such as educational attainment and gender. Subsequently, a more scientifically grounded approach was employed, combining the K-means algorithm and PSO with actual land use considerations, aiming for enhanced equity and minimized walking distance. Multiple iterations were conducted to determine the location and area of new UPGS with greater practical significance, and the validity of the optimization method was verified through measurement statistics. This study demonstrates both the feasibility and limitations of our accessibility measurement model within a research framework for evaluating UPGS accessibility and equity in Nanchang City; moreover, it highlights that this framework and methodology can be flexibly applied to other cities utilizing reasonable data.

It is worth noting that there is still considerable flexibility in determining the final area and location of the new UPGS. In addition to ensuring that the k-means algorithm results closely approximate the minimum distance in practical scenarios, it is essential to consider the following recommendations: (1) In densely populated and congested urban settings, new UPGS additions should primarily take the form of community parks, with a more significant proportion of hard surface area to enhance UPGS accessibility and tourist capacity. Additionally, addressing the pressure on UPGS supply can be achieved through developing rooftop gardens or sharing certain types of open spaces (such as those in communities and educational institutions) [73]. (2) When the k-means algorithm results are close to existing UPGS locations, increasing the area of existing UPGS or modifying the internal hard surface areas can enhance park service capacity. Previous research has shown that transforming existing parks can enhance the fairness of park resource utilization [74]. (3) For suburban residential areas with zero accessibility and poor urban connectivity, improving the service capacity of road networks is more effective than adding new UPGS. (4) Since the ESVs and PCs of UPGS also affect residents' willingness to choose and limit the number of residents [3, 30], the service capacity of UPGS can all be enhanced by increasing the number, type, and patch quality of facilities within UPGS. Apart from the research outcomes, this paper has certain limitations. First, no established metric exists in model optimization to quantify the substitution effect of landscape pattern indices and hard surface area in place of ESV and PCs. Furthermore, the determination of the UPGS service radius was made hastily. Currently, mobile phone signal data can provide the movement trajectories of UPGS users, allowing for the identification of more precise UPGS service radii [25, 75]. Third, other modes of transportation, such as cycling, public transit, automobiles, and subway travel [47], were not considered. Finally, there is still significant flexibility in determining the location of the new UPGS. Future research could potentially involve the development of an app that integrates local land use planning and input regarding existing UPGS supply and demand to calculate new UPGS location information directly.

7 Conclusion

In this study, taking Nanchang City as an example, we have developed a systematic procedure and framework for constructing the accessibility analysis and fairness evaluation and optimization of UPGS based on multi-source big data. By combining the

improved G2SFCA model with K-means and PSO algorithms, we have obtained more accurate and objective and reasonable results. Through such objective factors as landscape pattern index and UPGS hard site area, the quality attributes ESV and PCs of the UPGS itself are estimated and incorporated into the existing G2SFCA accessibility measurement model to comprehensively analyze the spatial distribution characteristics of the accessibility level of the UPGS in the study area. The results show that the distribution of UPGS accessibility in Nanchang is uneven, generally showing a spatial pattern of decreasing from east, south, and west towards the center. The spatial autocorrelation model between socioeconomic status and accessibility is used to uncover the degree of spatial coupling between the two. A significant positive correlation was found between socio-economic level and UPGS accessibility. On this basis, the community is used as a medium to couple the pending optimization objectives of spatial and social equity, and 29 new UPGS with specific locations and areas are obtained by combining the K-means algorithm with the particle swarm algorithm based on the land use data of Nanchang City. The optimization process is highly reliable and easy to operate and applies to the optimization of UPGS accessibility in other cities, which is beneficial for urban planners to develop effective improvement strategies for poorly served communities to achieve equity in the UPGS enjoyed by all residents within the city.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

YZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing - original draft, Writing - review & editing. PG: Funding acquisition, Resources, Supervision, Writing - review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Jin, C.T. Green space provision and allocation for sustainable growth of compact cities. *Cities* (2006) 23:111–20. doi: 10.1016/j.cities.2006.04.004
- Miles, M., Brindley, P., Makawane, R., Ferguson, A. Understanding the socioeconomic equity of publicly accessible greenspace distribution: the example of Sheffield, UK. *Governance* (2019) 105:129–47. doi: 10.1016/j.govern.2019.04.016
- Tang, Y., He, R., Tan, G., Wang, X., Fiksel, A., Ishihara, A. Equity study on Urban Park accessibility based on improved 2SPCA method in Jiangsu, China. *Land* (2022) 11:2043. doi: 10.3390/land11122043
- Chen, M. Place value, place quality and its impact on health, social, economic and environmental outcomes. *J Urban Des* (2019) 24:1–46. doi: 10.1080/13574809.2018.1472429
- Chen, A. The role of urban parks for the sustainable city. *Landsc Urban Plan* (2010) 94:129–36. doi: 10.1016/j.landurbplan.2010.05.003
- Huang, J., Liu, J., Tan, Z., Tang, Z. Evaluation of park green space accessibility in Shenzhen from the perspective of social equity. *Sci Geogr* (2022) 42:896–908. doi: 10.10240/j.1000-0527.2022.02.005
- Zhao, C.H., Zhang, Y. Urban Park layout formation method in high density cities. *Chinese Landscape Architecture* (2021) 37:64–70. doi: 10.19753/j.cha.2021.10.006
- Li, W., Bai, Y., Zhao, W., Han, C., Tian, L. Land use significantly affects the distribution of urban green space: case study of Shanghai, China. *J Urban Plan Dev* (2015) 143:44014405. doi: 10.1061/(ASCE)UP.2190.4444.04000144
- Aguyun, J., Ford, B. Fair sustainability: the missing dimension of neo-neoliberal justice in urban geography. *J Urban Geogr* (2019) 47:375–44. doi: 10.1111/j.0278-6628.2018.00127.x
- Niu, S., Tang, S.M. Research on the equity measurement of park green space distribution in high-density urban areas—a case study of Hangzhou district, Shanghai. *China Landsc. Archit.* (2011) 37:109–15. doi: 10.19753/j.cha.2011.10.010
- Jiang, H., Zhao, C., Gao, B. Advances in the equity of spatial distribution of urban public service in western countries II. *City Plan. Rev.* (2015) 35:72–77
- Hansen, W.G. How accessibility shapes land use. *J Am Stat Assoc.* (1959) 54:232–46. doi: 10.1080/01621459.1959.10507307
- Peng, S., Chen, L., Sun, B., Peng, Z., Li, L., Xiao, M., et al. The distribution and accessibility of urban parks in Beijing, China: implications of social equity. *Int Environ Res Public Health* (2019) 16:8894. doi: 10.3390/ijerph16248894
- Gong, C.E., Delmuth, D.M., Delmuth, B.C. Are corresponding accessibility to parks in multi-modal cities a variable with housing catchment area (TPCA) method. *Landsc Urban Plan* (2015) 144:96–9. doi: 10.1016/j.landurbplan.2015.06.014
- Giles, E., Anselin, L. Assessing spatial equity: an evaluation of measures of accessibility to public programs. *Environ Plan A* (1990) 22:665–675. doi: 10.1080/01909369008908
- Tobin, J. Violating fairness, equity maps for planners. *J Am Plan Assoc.* (1998) 64:22–30. doi: 10.1080/01909369808907554
- National Recreation and Park Association. *Parks of America in underserved areas: A public health perspective. National Recreation and park association. Library.* USA, VA (2011)
- Wimmerich, H., Kabisch, S., Kabisch, J. Access to urban green space and environmental inequalities in Germany. *Landsc Urban Plan* (2017) 164:124–31. doi: 10.1016/j.landurbplan.2017.06.002
- Xu, B., An, Z., Zhang, Y., Li, Z. Healthy aging with parks: association between park accessibility and the health status of older adults in urban China. *Environ Urban Res* (2019) 45:45–66. doi: 10.1016/j.enur.2019.06.010
- Gao, S., Song, Y., He, T., Li, Y., Ma, T., Ju, Y., et al. Accessibility to urban parks for elderly residents: perspectives from mobile phone data. *Landsc Urban Plan* (2019) 185:10342. doi: 10.1016/j.landurbplan.2019.10342
- Swann, J.C. Demographic generation: evidence and applications. *Geoweb* (1948) 11:11–18. doi: 10.1080/20434468
- Pain, A., Cook, D.M., Mowery, C. Measuring accessibility: positive and negative implications of various accessibility indicators. *J Transp Geogr* (2012) 28:111–23. doi: 10.1016/j.jtrangeo.2012.03.018
- Shan, A.A. An integrated approach to measuring potential spatial access to health care services. *Environ Plan B* (1992) 20:75–87. doi: 10.1080/01441649208739000
- Nykula, S. Measuring the accessibility and equity of public traffic: a case study using GIS. *Internat J. Geogr. Inf. Sci.* (2011) 35:321–34. doi: 10.1080/01448758.2011.588862
- McCauley, G.R., Beck, M., Tisdale, A.S., Dignall, B. Characteristics of urban parks associated with park use and physical activity: a review of qualitative research. *Health Place* (2010) 16:712–20. doi: 10.1016/j.healthplace.2010.09.007
- Arif, A.K., Hameed, A.R., Ghady, K.L., Memon, S.A., Arif, P. Not just a walk in the park: methodological improvements for determining environmental justice implications of park access in New York City for the promotion of physical activity. *Cities Environ* (2018) 8:1–17. doi: 10.1016/j.cities.2018.11.001
- Rodriguez, L., Ma, L. Spatial distributions, modeling and mapping urban regions to predict access to social programs. *Geographic Sci* (2010) 3:105–12. doi: 10.1007/s10465-010-9107-4
- Zhao, W., Yao, Z., Mao, D. Spatial accessibility analysis of urban green space under walking condition in Xijitong river urban area based on 2SPCA. *J Planning Econ Dev* (2022) 40:227
- Hallgren, M., Patten, T., Ivette, C., Jones, A. The relationship between access and quality of urban green space with population physical activity. *Public Health* (2018) 150:1127–32. doi: 10.1016/j.puhe.2018.10.007
- Tang, Z.H., Chen, W., Chen, Q., Zhang, L. Measurement of spatial accessibility to health care facilities and defining health professional shortage areas based on improved potential mobility: a case study of taidong county in Jiangsu province. *Sci Geogr* (2018) 38:1115–20. doi: 10.13249/j.cnki.scigeo.2018.02.013
- Fremont, K., Norstrom, J., De Maeyer, P., Delmuth, G. A continuous-based two-step floating catchment area method for measuring spatial accessibility of day-care centers. *Health Place* (2012) 17:67–75. doi: 10.1016/j.healthplace.2012.01.001
- Chen, H., Wang, S. Geographic disparities in accessibility to food stores in Southwest Missouri. *Environ Plan B* (2011) 38:619–27. doi: 10.1080/014416410.03140
- Luo, W., Qi, L. An enhanced two-step floating catchment area (2SFCA) method for measuring spatial accessibility to primary care physicians. *Health Place* (2009) 15:1190–7. doi: 10.1016/j.healthplace.2008.08.002
- Luo, W., Wiggins, J. Variable catchment sizes for the two-step floating catchment area (2SFCA) method. *Health Place* (2012) 18:799–95. doi: 10.1016/j.healthplace.2012.04.002
- Xing, L., Liu, Y., Wang, B., Wang, T., Liu, H. An environmental justice study on spatial access to parks for youth by using an improved 2SPCA method in Wuhan, China. *Cities* (2020) 96:102801. doi: 10.1016/j.cities.2019.102801
- Wang, Z., Li, Z., Zhang, H. The equity of Urban Park green space accessibility in large Chinese cities: a case study of Wuhan City. *Prog Geogr.* (2022) 41:823–35. doi: 10.18306/1002-152X.2022.04.007
- Chen, D. Racial/ethnic and socioeconomic disparities in urban green space accessibility: where to intervene? *Landsc Urban Plan* (2011) 100:234–44. doi: 10.1016/j.landurbplan.2011.01.002
- Giles, C.W., Brown, J.H., Kremen, M., Collins, C., Douglas, K., Ng, K., et al. Increasing walking: how important is distance to destinations, and size of public open space? *Am J Prev Med* (2010) 28:140–50. doi: 10.1016/j.amepre.2010.03.014
- Qiu, H., He, J.B., Zhang, L., Wang, S. Comprehensive evaluation of accessibility of urban parks in Nanjing. *Landscape Arch* (2022) 30:76–86
- Estadler, S. To choose a house means to choose a lifestyle: the assumptions of housing and class stratification in urban China City Soc (2017) 19:287–311
- Tian, H., Jingran, H., Haiguan, Y., Xiao, Q. Evaluating the impact of urban bias space accessibility on housing price: a spatial quantile regression approach applied in Changsha, China. *Front Environ Sci* (2021) 9:164. doi: 10.3389/fenv.2021.699426
- Long, Y., Qin, L., Wu, X., Wang, K. Analysis of Urban Park accessibility based on space syntax take the urban area of Changsha City as an example. *Land* (2021) 10:390. doi: 10.3390/land10050390
- Zhang, S., Yu, H., Chen, Y., Jing, Y., Zeng, F. Accessibility of park green space in Wuhan, China: implications for spatial equity in the post COVID-19 era. *Int J Environ Res Public Health* (2022) 19:5446. doi: 10.3390/ijerph19095446
- Chen, Y., Yao, W., Li, B., Mao, D. Which communities have better accessibility to green space? An investigation into environmental inequality using big data. *Landsc Urban Plan* (2022) 216:104504. doi: 10.1016/j.landurbplan.2022.104504
- Xiao, Y., Wang, Z., Li, Z., Tang, Z. An assessment of urban park access in Shanghai—implications for the social equity in urban China. *Landsc Urban Plan* (2017) 152:383–95. doi: 10.1016/j.landurbplan.2016.05.007
- Xu, M., Sun, J., Su, S., Wang, M., Cao, Z. Social inequalities of park accessibility in Shanghai, China: the role of park quality, transport modes, and hierarchical socioeconomic characteristics. *J Transp Geogr* (2017) 62:34–39. doi: 10.1016/j.jtrangeo.2017.05.018
- Tang, D., Fan, Y., Su, H. Evaluation of green space accessibility based on improved Gaussian two-step floating catchment area method: a case study of Jinzhong City, China. *Chin Geogr* (2021) 46:1113–20. doi: 10.1002/ajgg.2021.07.004

46. Wu C, Huang C, Li J, Xu L. An evaluation model for urban carrying capacity: a case study of China's megacities. *Sustain* (2018) 10:287–96. doi: 10.3390/s10180287
47. Ueda K, Shengyan Y, Chen C, Huan H, Han L. Accessibility evaluation and layout optimization of urban parks in Sijie District, Nanjing City based on walking of the elderly people. *Landscape Res*. (2020) 12.
48. Van Bommel A, Meisemann T. A monitoring tool for the provision of accessible and attractive urban green spaces. *Landscape Urban Plan*. (2019) 183:108–26. doi: 10.1016/j.landurbplan.2019.06.019
49. Bai J, Wang Y. Spatial accessibility of park green space in Hongqiao District of Shanghai based on modified two-step floating catchment area method. *Prog Geogr*. (2022) 41:776–89. doi: 10.18306/1000-0527.2021.03.001
50. Brown GL, Buckley GL, Green JB, Isaac C. Parks and people: an environmental justice inquiry in Baltimore, Maryland. *Urban Aff Aff*. (2019) 49:547–67. doi: 10.1080/00141801.2019.1622849
51. Du Q, Wang Y, Xu S, Wu H, Tang X. Detailed assessment of the spatial distribution of urban parks according to day and travel mode based on web mapping API: a case study of main parks in Wuhan. *Int J Environ Res Public Health*. (2018) 15:273. doi: 10.3390/ijerph15092733
52. Li M, Liang L. Relationship between supply and demand of green open space in Shanghai District of Beijing based on accessibility. *Beijing Geogr*. (2022) 45:108–17.
53. Wang C, Guo JL, Guo DQ. Research on urban spatial structure in Beijing based on housing prices. *Prog Geogr*. (2014) 33:2222–31.
54. Li H, Wu YD, Wu Y, Tang Y. Analyzing housing prices in Shanghai with open data, amenity, accessibility and urban structure. *Cities*. (2019) 91:550–76. doi: 10.1016/j.cities.2018.11.014
55. Wang M, Li L, Su Y. Spatial data analysis case-based experimental (volume). (2019)
56. Wu W, Ding K. Optimization strategy for parks and green spaces in Huzhou City: improving the supply quality and accessibility. *Int J Environ Res Public Health*. (2022) 19:4443. doi: 10.3390/ijerph19094443
57. Li Z, He W, Zhang M, He J, Tang Y, Zhang H, Sun C. The first 1-meter resolution national-scale land cover map of China created with the deep-learning framework and open access data. *Earth Environ Science Data Discussion*. (2023) 2023:1–38.
58. Li L, Du Q, Ren F, Ma X. Assessing spatial accessibility to bicycled urban paths by multi-type of travel distance in Shanghai, China. *Int J Environ Res Public Health*. (2019) 16:3108. doi: 10.3390/ijerph16093108
59. Zhang J, Zhang H, Li J, Wu Y, Zhao B. Highlighting the changes in residential exposure to green spaces: the case of a rapidly urbanizing metropolitan region. *Health Environ*. (2021) 188:102700. doi: 10.1016/j.healthenv.2020.102700
60. Wang J, Foley K. Assessing the performance of urban open space for achieving sustainable and resilient cities: a pilot study of two urban paths in Dublin, Ireland. *Urban For Urban Green*. (2022) 62:127196. doi: 10.1016/j.ufug.2021.127196
61. Black N, Maitre M, Haddi J, Okunribi R. Urban and rural geography of aging: a local spatial interaction analysis of aging population movements. *Urban Geogr*. (2018) 43:409–28. doi: 10.1080/02723636.2014.912294
62. Zhao R, Li LL, Cao L. GIS-based analysis of city park green space service range and layout optimization: a case study in Haidian international business city. *Chin Landscape Arch*. (2015) 31:95–9.
63. MacQueen J. Some methods for classification and analysis of multivariate observations. *Proceedings of the 4th Berkeley symposium on mathematical statistics and probability* (1967). 1–281–297.
64. Chen M. The swarm and the queue: towards a distributed and adaptive particle swarm optimization. *Proceedings of the 1999 congress on evolutionary computation: CEC-99 (vol. 3)*. No. 97114466. IEEE; (1999). p. 2201–2207.
65. Stock HH. Clustering methods: a history of k-means algorithms, selected contributions to data analysis and classification. *Appl Artif Intell*. (2007) 21:443–72. doi: 10.1080/0898/2.3.4021366.1_35
66. Liu Z, Zhang W, Wang Z. Optimal planning of charging station for electric vehicle based on quantum PSO algorithm. *Chin J Electr Eng*. (2012) 48:1349–57. doi: 10.13334/j.1024-6460.2012.21.004
67. Zhang J. Evaluating spatial disparity of access to public paths in urban and open communities with an improved G2H-G3 model. *Sustain*. (2019) 11:1940. doi: 10.3390/s11111940
68. Shi L, Xing L, Bai Y, Hu Q. Spatial optimization of park green spaces by an improved two-step optimization model from the perspective of maximizing accessibility equity. *Land*. (2023) 12:948. doi: 10.3390/land12030948
69. Ma JD, Cao X. A GIS-based evaluation method for accessibility of urban public green landscape. *Acta Sci Nat Sin*. (2005) 45:111–5.
70. Ma J, Yueh J, K. Greenways: H. H. Yuen's. *Appl Geogr*. (2019) 107:107–12. doi: 10.1016/j.apgeog.2019.101725
71. Zhang J. Urban green landscape parks for sustainable cities. *Int J Urban Res*. (2012)
72. Wu H. *Planning of public open space in urban spatial structure*. *J Environ Res Manag*. (2003) 46:298–305. doi: 10.1016/S0895-0940(03)00023-8
73. Liu Y, Zhou Y, Lin H, Wu S, Li B. Exploring the disparities in park accessibility through visible phone data: evidence from Fuzhou of China. *J Environ Manag*. (2021) 281:113849. doi: 10.1016/j.jenvman.2021.113849



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Human aeroecology

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ABSTRACT

human aeroecology, human airspace ecology, perihuman environment, biotransphere, air
quality, multisensory communication, multimodal communication, pathogen transmission

Introduction

Airspace has been recognized as *habitat* for at least a decade (Smith, 2013). However, the ecology of airspace has generally been defined with respect to airborne lifeforms such as birds and insects (e.g., Chelton et al., 2017). Humans are as much creatures of the air as lifeforms that walk the ocean floor are creatures of the sea. Yet, little is understood about the full scope of human interaction with the airspace, much of which is normally invisible and intangible. Topics relating to human aeroecology have long remained isolated at the periphery of many disparate fields. For example, humans interact biophysically with the air in obvious ways, as through breathing and heat loss, but also through releasing particulates (shed skin cells and clothing fibers) and inhaling and releasing airborne organisms (viruses, *strep* bacteria, and body-dwelling insects) and allergens. Humans interact with other humans through the air by speaking and through transfer of volatiles (perfumes, body odor, and pheromones). These chemical interactions can be strong and person-to-person over short distances, or weaker and affecting larger numbers of people over room-scale distances.

The importance of airborne cross-infection in the COVID-19 pandemic spurred much investment into research on human airspaces, and in response many researchers began pushing across divides between traditional disciplines involved in understanding the complex relationships between humans and the airspaces we live in and share. Partly as a result of this cross-pollination, a new interdisciplinary field is emerging, which we here call Human Aeroecology. Articulating the bounds of this field will, in our opinion, provide a conceptual framework enabling the development of new research questions and identification of common ground and connections between previously disconnected areas of study.

The portion of the aeroecology that humans normally occupy, or perihuman environment (Hixon et al., 2007), is equivalent to the benthic zone in marine ecology terms. Of the vast aeroecological habitat of the troposphere, this human-adjacent hemisphère is shared with countless other terrestrial and airborne organisms whose functions and relations in this zone extend beyond the scope of the present paper, but unquestionably demand attention. Within this sphere, human aeroecology conceptually addresses not just interactions with the air proper, but also aspects of the air as a medium and as a living space, including (but not limited to) areas typically associated with human

atmospheric ecology (Weighman, 2000; Paine, 2017), visual ecology (Asher et al., 2022), and combined sensory ecology (Le Maho et al., 2017). We hope the present work can begin to shape a more convergent dialogue around this vital area, enabling the creation of human airspaces that reflect a deeper understanding of human health, communication, and human experience within our aerocology.

Here we identify five broad areas within human aerocology that researchers have developed over the past years, and which we argue would benefit from focused collaboration. These include but are not limited to: Airscape Design, Air Quality for Comfort, Health, Education and Productivity (Air Quality for CHaEP), Shared Airspaces for Social Connection, Auditory, Aerotactile, Olfactory, and Visual Communication, and Pathogen Transmission, as seen in Figure 1.

Some areas of inquiry in human aerocology

Airscape design

Indoor and outdoor air quality is essential in human aerocology. There is active work in the use of transportation (Gao et al., 2020), placement of parks and water (Cui and Lu, 2023), landscaping (Commins et al., 2013), phytoremediation (Bilem et al., 2020), outdoor air systems (Machuga, 2001), and roofing (Vaidyanathan, 2016) to control outdoor heat, humidity, CO₂, vapors, and particulates.

Focusing on one source of particulates. At the room or outdoor BBQ/stovefront level, cooking produces typically pleasant social signals (Dindigs and Noller, 2018), is used as a lure for social and commercial interaction (Morris, 2011), yet is a sign of hazard when something is burning due to smoke.

Outdoor air control, exchange (of outdoor and indoor air, outdoor (Tao et al., 2021) and indoor humidity control (Boughton and Arora, 1998), indoor ventilation (Aubrey et al., 2013), heating and cooling (Zhou et al., 2022), oxygen production and CO₂ removal (Kozma et al., 2000) are studied to control indoor atmosphere, pathogens (Alkham, 2009), and mold (CFC, 2023). Airscape design also includes intentional design of soundscape factors, which are known to affect well-being (Madsen et al., 2013). Done well, good airscape design facilitates Air Quality for CHaEP.

Air quality for comfort, health, education, and productivity

Indoor air quality for CHaEP involves creating indoor environments that facilitate comfortable temperatures and air circulation, limit pathogen spread, facilitate effective communication, and nurture social and work-supporting connections. Design methods include controlling ventilation, insulation (Kumar et al., 2020), and airflow control to facilitate comfort (Thom, 2016), reduce noise (see

De Jans et al., 2002), control odor (see Marino and Sherman, 2004), and mitigate pathogen spread through effective air supply (Parish and Tauxe, 2013). Both the ventilation flow rate and the direction of flow are important. Improving indoor air quality in this way promotes comfort (Jia et al., 2021), health (Gould and Martello, 2017), productivity (Wong, 2004), and learning (Pulman et al., 2010; Sefraoui et al., 2021). In the sensory space, noise pollution also negatively impacts learning (Clare et al., 2013), and good acoustics enhance a mild sense of calm (Janda and Tjebk, 2000). We argue that a holistic design approach including all of these factors is essential for creating airspaces that promote Social Connection and Development.

Shared airspaces for social connection

While we know how important it is to make airspace comfortable and safe, we are in the early days of understanding how being in a shared airspace facilitates social connection and development. New research into brain activity (Zhou et al., 2023) shows the importance of in-person interactions. Shared airspaces must be well-lit (Manning et al., 2017), have good acoustics (Raman et al., 2017), have good air quality (Wargacki et al., 2020) and facilitate airflow (Cao et al., 2014) to facilitate human comfort (see Malhotra, 2013), learning (Wargacki et al., 2020), and largely unstudied connections to community and social interactions.

As an example, even pleasant particulate matter emitted from cooking can be harmful to cooks (Tschentschke et al., 2017), particularly if the cooking temperature is too high for the oil used, or the cooking fuel burns inefficiently. These aerosols can increase "acute pulmonary illness, asthma, cardiovascular disease, and lung cancer" amongst those doing the cooking (Tschentschke et al., 2023). Cooking aerosols are also a significant portion of nearby outdoor particulate matter (Abdullahi et al., 2013). Ventilation, lower emission fuels, careful cooking, and even the instruments that are part of Internet of Things (Burns et al., 2023), can be used to mitigate these risks, in a manner that recognizes that there are many costs and benefits to the effects of cooking on shared airspaces.

The "personal cloud" in human-adjacent airspaces simultaneously facilitates deleterious volatile particle inhalation (Liu et al., 2017; Parvizi et al., 2020) and useful olfactory communication (Roberts et al., 2023), so it must be carefully managed. We argue that this is perhaps the least studied of the five broad categories of human aerocology we list here, and improved understanding of shared airspaces has the potential to produce massive social benefits to humanity due to the impacts on Auditory, Aerotactile, Olfactory, and Visual Communication.

Auditory, aerotactile, olfactory, and visual communication

Shared aerocology is especially important for human communication and interaction. In addition to the airspace

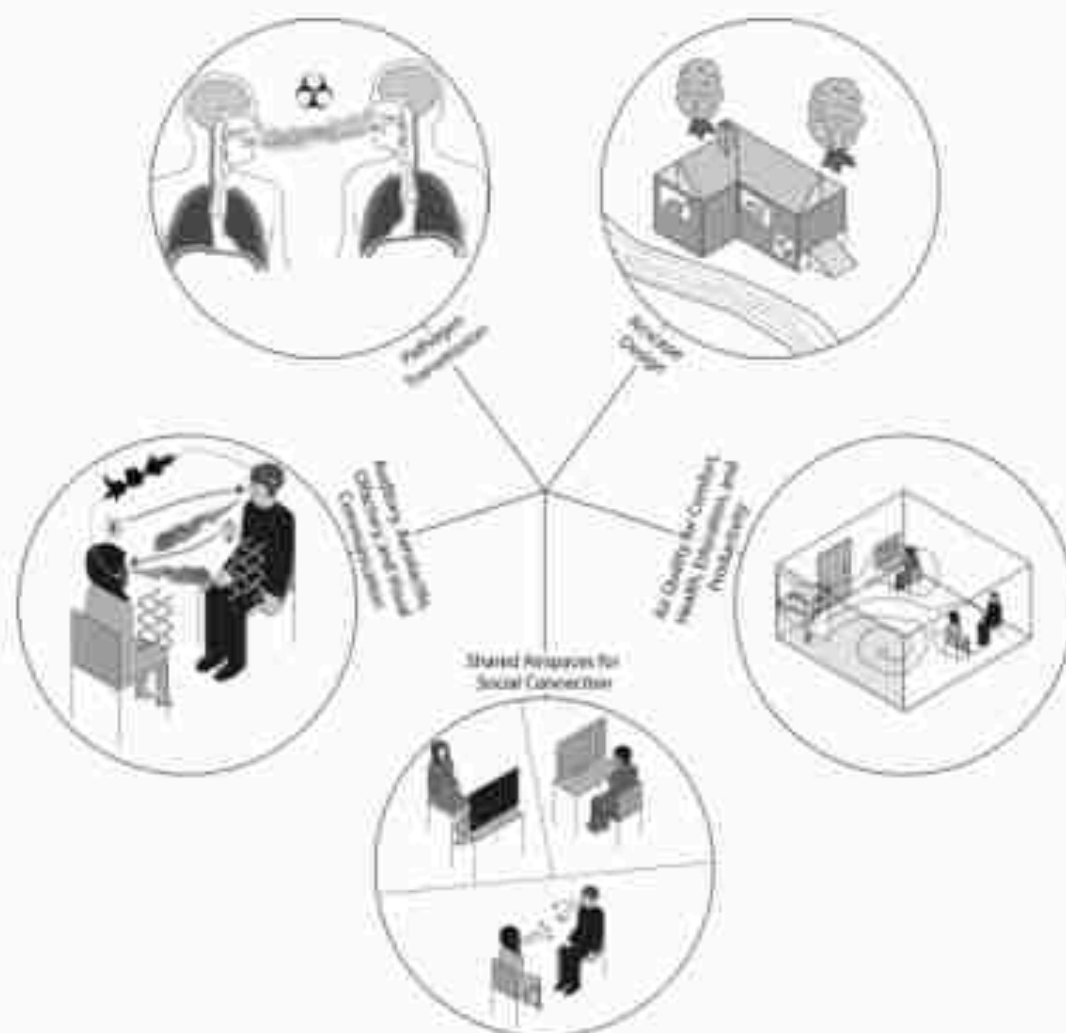


FIGURE 2
A conceptual diagram of human ecology and pathogen transmission.

providing the medium of spoken and visual communication, subtle information from speech airflow affects auditory speech perception (Derrick et al., 2019; Cook and Derrick, 2019), interacting with visual and auditory information (Koussy et al., 2010; Derrick et al., 2019). While we have seen limitations in the effect of airflow on speech (Derrick et al., 2019; Hansmann et al., 2021), we know that speech airflow itself conveys speech information that adds to auditory and visual speech (Borowski et al., 2010; Derrick et al., 2019), and interacts with speech perception along the autism spectrum (Derrick et al., 2019a). The airflow also contributes heat (Derrick et al., 2022) and communicative smells (Koussy, Adams and El Hachimi, 2020; Robert et al., 2020). Given that face masks limit (Compagnon, 2021; Derrick et al., 2021), and distance meetings diminish these communicative advantages, sometimes leading to subjective sense of fatigue (Bilicini et al., 2022; Gohar, Soudani and Wabait, 2022), the study of *Airspace Design*, *Air Quality for CHOP*, and *Shared Airspace for Social Connection* all provide many of the most useful tools to help control Pathogen Transmission.

Pathogen transmission

Breathing, talking (Derrick et al., 2022), singing (Ajzoud et al., 2022), coughing (Li et al., 2021), and medical therapies (Gering et al., 2021) all move air and can spread pathogens and allergens (Levine et al., 2022). We know that, in increasing efficacy, surgical masks, respirators (Adams et al., 2021) and especially FFP3 suits can reduce pathogen transmission and have long been a part of hospital protocol in high-pathogen environments. However, face masks cover the face, block some heat transfer and most speech airflow (Derrick et al., 2022), and muffle speech (Mayer et al., 2020). Because of this, effective personal protective equipment impedes good communication (Twiss and Twiss, 2021), and contributes other largely under-appreciated stresses to the users (Compagnon, 2021).

Therefore, a human ecology approach has long been proposed for studying the costs and benefits of interventions in airborne pathogen transmission (e.g., Wells, 1971; Yan et al., 2014).

Specific findings (Yoon et al., 2018) indicate the need for careful and nuanced consideration of patient access based on the interaction of pathogen transmission and pathogen breakthrough infection after vaccination). Overall, recent findings on airborne transmission (reviewed by Simonson et al., 2023), underscore the benefits of an interdisciplinary approach to understanding pathogen dissemination within shared spaces, with implications for infection control and public health. The best protocols often lead back to control of Airspace Design and Air Quality for CHSEP.

Research methods in human aeroecology

These interconnected fields of research incorporate an astonishing array of methodologies, which include but are not limited to indoor and outdoor environmental modeling (Jensen and Hutterer, 2007), behavioral studies (Rosen, 2014), EEG for neural responses to indoor and outdoor environments (Shim et al., 2018), modeling and simulation of gas and particulate transport (CFD) (Mallamaci and Fanti, 2022; Tan et al., 2022; Xing et al., 2022), measurement of microbes, trace species, and particulate flow with schlieren (Van et al., 2011), particle samplers (Wang et al., 2020), study of colony forming units for pathogens (e.g., Lukow et al., 2010), DNA analysis of airborne microorganisms (Parnham et al., 2015), and volatile compound samplers (Jiao et al., 2009). Therefore the technical span of human aeroecology matches the disciplinary span, supporting the need for a conceptual connection across these multivariate fields of research.

Conclusion

Human aeroecology is emerging as a transformative interdisciplinary field, integrating knowledge spanning many traditional disciplines. The need for a more clearly articulated paradigm for this field has been underscored by the recent pandemic, and demands a holistic approach to studying and shaping the spaces we collectively inhabit. We recommend: 1) Attaching keywords to research so that topics in human aeroecology are easier to identify; 2) Intentional wide-ranging

research collaboration in human aeroecology; 3) Conferences and conference sessions on human aeroecology; and 4) Documentation and communication of the benefits of careful human aeroecology in urban and building design.

Author contributions

DD: Conceptualization, Writing – original draft, Writing – review & editing. BG: Conceptualization, Writing – original draft, Writing – review & editing. MJ: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Abdellatif, R. E., Delgado Salazar, J. M., and Martinez R. M. (2015). Emission and intake concentrations of particulate matter and its specific chemical components from cooking. *Atmos. Environ.* 75, 240–246. doi: 10.1016/j.atmosenv.2013.11.041
- Ackley, A., Gimple, L., Chou, J., MacKinnon, S., Hattendorf, A., Jones, K., et al. (2012). *The Effectiveness of Natural Ventilation: A case study of a typical New Zealand classroom with residential occupancy*. New Zealand Ministry of Education (Wellington, New Zealand). Te Hanga Waka Victoria University of Wellington.
- Akinci, A., and H. B. (2020). Optimal design of classroom spaces in naturally-ventilated buildings to maximize occupied ventilation with human health and body activity. *Built Environ.* 149, 106–121. doi: 10.1016/j.builtenv.2019.106119
- Alves, M., Natusch, A., Bellini, R., Bucher, R., Bergsson, F. E., Espedal, C. J., et al. (2020). Inhalable respiratory particles during singing and talking. *Atmos. Environ.* 94, 1201–1208. doi: 10.1016/j.atmosenv.2019.120102
- Allen, D., Baskerville, K., Pegg, D., Goryainov, A., and Kuvshinov, V. (2022). In *Intelligent Assessment of the Social Ecology of the Urban Environment and International Conference on Technological Advancement in Computational Science (ICTACS)*. Tadjikistan: Hindustan, 362–366. doi: 10.1109/ICTACS4279.2022.9866672
- Alison, J. (2009). Natural ventilation for infection control in health-care settings. *World Health Organization*.
- Arino, K., Kato, N., Saito, Y., and Ogasawara, H. (2018). Effects of low-level influenza exposure in carbon dioxide in indoor environments: A short review on human health and psychomotor performance. *Environ.* 164, 121–134. doi: 10.1016/j.envint.2018.08.024
- Burns, R. R. (2011). Behavioral change, indoor air pollution and child respiratory health in developing countries: a review. *Int. J. Environ. Res. Public Health* 11, 1617–1618. doi: 10.3390/ijerph11010617

- Baughmans, A., and Aerts, E. A. (1996). *Indoor Acoustics and human health: Part I. Different views of health effects of Acoustics influenced indoor pollution* (Brussels: Centre for Indoor Environment).
- Bavarski, E., Derrick, D., and Glick, B. (2010). Virtual tactile integration in speech perception facilitates for readability (natural speech perception). *J. Acoust. Soc. America* 128, 3522–3529. doi: 10.1121/1.3461980
- Bridges, M., and Ballie, L. M. L. (2019). *Food aroma evolution: During food processing, cooking, and aging* (Boca Raton, USA: CRC Press). doi: 10.1201/9781043441447
- Campagna, D. M. (2021). The problem with commensalities: pests from face masks. *J. Appl. Ecol.* 8, 130069. doi: 10.1016/j.jae.2021.100069
- Guo, G., Jishi, H., Yao, X., Zou, Y., Sun, K., Suwan, R., et al. (2019). A review of the performance of different ventilation and airflow distribution systems in buildings. *Build. Environ.* 157, 171–184. doi: 10.1016/j.buildenv.2019.121999
- Centers for Disease Control (CDC). *Mold Testing and Prevention* (Atlanta, Georgia, USA: United States). Available at: <https://www.cdc.gov/mold/hygieneandremediation/index.html>
- Chen, J., Kelly, A., Williams, S., Jorgensen, J., Vermeulen, E., Peggmann, M., et al. (2022). Classroom Ventilation: The Effectiveness of Filtering and Hybrid Systems: An analysis of 107 spaces in 13 schools across New Zealand. New Zealand Ministry of Education (Wellington, New Zealand). Te Hanga Waka Whiria University of Wellington.
- Childs, P. R., Poth, W. F., Kelly, J. F., and Lachin, F. (2017). *Acoustics* (Berlin: Springer). doi: 10.1007/978-1-447-04070-2
- Cicchelli, A., and Marshini, T. (2017). Indirect on quality and health. *Int. J. Environ. Res. Public Health* 15, 4533–4544. doi: 10.3390/ijerph15112286
- Collins, A. P., Ieremia, B. C., Harris, S., Mithani, N., Yang, L. M., Oshin, D. C., et al. (2022). 3D printing and rapid prototyping effectiveness against respiratory viral diseases in the healthcare setting: A systematic review and meta-analysis. *J. Am. Coll. Emergency Physicians* 3, 12582. doi: 10.3389/jcep.12582
- Crabtree, J. P., Gahleitner, C. S., and Chow, W. Y. L. (2019). Indirect ventilation and urban heat island effect: Assessing the relationship between landscape characteristics and local surface temperature in Phoenix, Arizona. *Landscape Ecol.* 34, 171–183. doi: 10.1007/s10681-012-9403-1
- Crooks, R., and Tress, J. (2010). Architectural: a systematic review. *R. Soc. Open Sci.* 7, 463–470.
- Derrick, D., Anderson, P., Glick, B., and Green, A. (2010). Characteristics of speech produced in English 'ps'. Experiments and simulations. *J. Acoust. Soc. America* 125, 2272–2281. doi: 10.1121/1.3401406
- Derrick, D., Daverius, R., and Glick, B. (2019). Virtual tactile speech perception and the urban quarter. *Front. Commun.* 5, doi: 10.3389/fcomm.2019.00001
- Derrick, D., Hanson, D., and Thers, C. (2016). To model speech: Audio-tactile integration in speech perception. *J. Acoust. Soc. America* 140, 3485–3504. doi: 10.1121/1.3514094
- Derrick, D., Kishida, N., Longworth, L., Paine-Beardsley, P., and Jones, B. (2022). Speech on flow with and without face masks. *Sci. Rep.* 12, 1–10. doi: 10.1038/s41598-021-94767-2
- Derrick, D., Molyneux, T., and Thers, C. (2019). Audio-tactile integration during speech perception: Effects of response and stimulus characteristics on syllable identification. *J. Acoust. Soc. America* 146, 1603–1614. doi: 10.1121/1.5121131
- De Sola, M. H. P. L., Williams, D. J., and Sharples, S. (2022). Noise control strategies for naturally ventilated buildings. *Build. Environ.* 217, 109148. doi: 10.1016/j.buildenv.2021.109148
- Dodd, B. B. (2011). The whisper is habitat. *Trans. Ent. Soc. Am.* 28, 177–179. doi: 10.1016/j.tesa.2011.02.013
- Fryer, S. L., and Blessey, W. (2019). Studying relationships between noise and outdoor air quality. *J. Air Waste Manage. Assoc.* 69, 292–300. doi: 10.1080/10472693.2019.1634407
- Glick, B., and Derrick, D. (2010). Aero-tactile integration in speech perception. *Science* 327, 542–544. doi: 10.1126/science.1187722
- Grimshaw, S. A., Burton, M. P., Marsden, G., and Wallace, K. (2012). "Empirical bioclimatic microclimates," in *Manual of Environmental Microclimatology*, Fourth Edition. Ed. M. V. Yano, C. H. Nakano, R. V. Miller and S. D. Palla (John Wiley and Sons). doi: 10.1111/9781118160211.ch12
- Guo, Y., Zhang, Q., Lu, K. X., Zhang, T., Wang, S., and Zhang, M. (2020). The impact of urban temperature infrastructure on air quality. *Environmental* 12, 3629. doi: 10.3389/fenv.2021.6929
- Hartmann, D., Derrick, D., and Thers, C. (2021). Hearing, seeing, and feeling speech: the atmospheric vibrations of natural speech perception. *Front. Hum. Neurosci.* 15, 667789. doi: 10.3389/fnhum.2021.667789
- Jerry, M. C., Spencer, C. J. S., Brown, E. H., Derrick, J. F., Karabak, N., Gao, S., et al. (2021). Assessment of dispersion of airborne particles of controlled food by high flow nasal cannula therapy. *Ind. Eng. Res.* 60, 40246–40255. doi: 10.1021/acs.iecr.1c02465
- Kang, M., Derrick, D., and Glick, B. (2018). Close vocal effects on speech perception. *Acoust. Soc. America* 143, 1–19. doi: 10.1121/1.5069199
- Koch, M., Bergmann, E., and Lachmann, T. (2017). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Front. Psychol.* 8, 1607. doi: 10.3389/fpsyg.2017.00167
- Enner, D., Allen, M., Zou, F. X. W., Gargano, J. G., and Horton, R. A. (2020). Comparative analysis of building ventilation material properties and performance. *Renewable Energy* 151, 118078. doi: 10.1016/j.renene.2020.118078
- Lachmann, T. J., Miller, E., Ferraro, M., O'Brien, P., Cammarino, E., Choudhary, L., et al. (2021). Cooking particulate matter: A systematic review on respiratory exposure in the indoor cooking environment. *Atmosphere* 12, 12. doi: 10.3390/atmos12010012
- La Scola, E., Vanni, V. R. M. L., and Anelli, A. (2019). Landscape: a multi-sensor approach to improve the quality of urban spaces. *Energy Procedia* 78, 17–42. doi: 10.1016/j.eyspro.2019.11.111
- Levy, E., McLeod, J. E., Phipps, P., and Hirst, A. C. (2021). Air sampling and analysis of aerosolization: current and future approaches. *Curr. Allergy Asthma Rep.* 21, 223–239. doi: 10.1007/s12242-021-00071-2
- Li, H., Jiang, F. Y., Xu, G., Kang, C. W., Liu, K. H., Yan, H. H., et al. (2011). Airborne dispersion of droplets during coughing: A physical model of viral transmission. *Sci. Rep.* 1, 4637. doi: 10.1038/s41598-011-00245-2
- Lima, D., Tsch, Y., and Hauer, K. W. W. (2017). Immersion rates and the perceived sound effect associated with people release from the postpartum environment. *Indoor Air* 27, 791–802. doi: 10.1111/ina.12177
- Lin, H., Hong, Y., and Fumiko, T. (2021). Determining building indoor ventilation potential via IoT-based air quality sensors. *Front. Environ. Sci.* 9, 636. doi: 10.3389/fenv.2021.636770
- Lipson, H., Kuzibova, E. A., and Suterova, M. E. (2020). Acoustics of radiation with spin systems. *J. High Energy Phys.* 2020, 1–12. doi: 10.1088/1751-8058/ab900c
- Ma, N., Aze, D., Guo, H., and Ibrahim, M. W. (2021). Measuring the night factory: A review of variables and models for thermal comfort and indoor air quality. *Renewable Energy* 169, 110478. doi: 10.1016/j.renene.2021.110478
- Magee, M., Lewis, C., North, G., Rouse, H., Chan, J., Zeng, C. J., et al. (2020). Effects of face masks on acoustic analysis and speech perception: Implications for post-pandemic provision. *J. Acoust. Soc. America* 148, 3561–3568. doi: 10.1121/1.5100187
- Martens, K. E., and Sherman, M. H. (2008). *Why we breathe air* (Berkeley, California, USA: Lawrence Berkeley National Laboratory).
- McIntyre, G., Shepherd, G., and Harris, M. J. (2010). The economic potential of windpower: A physiological investigation. *Appl. Acoust.* 61, 10–24. doi: 10.1016/j.apacoust.2010.04.004
- Melcher, A. K. (2011). Human body micro-environment: The benefits of controlling indoor air quality. *Build. Environ.* 46, 79–77. doi: 10.1016/j.buildenv.2011.04.020
- Mitchell, F., and Bond, A. (2021). A review on applications of CFD modeling in COVID-19 pandemic. *Arch. Comput. Methods Eng.* 28, 3787–3796. doi: 10.1007/s10301-021-09700-1
- Morales, F., Francisco, G., Peña-García, A., Jardi, A., and Martínez-Aguado, F. (2017). Indoor lighting techniques: An overview of evolution and new trends in energy saving. *Energy Build.* 140, 50–60. doi: 10.1016/j.enbuild.2017.01.028
- Morris, M. (2011). "Smart marketing: An overview," in *Smart Marketing* (Thames, Oxfordshire, England, UK: Routledge). 71–86.
- Muñoz, S. A. (2011). Designing sustainable outdoor air systems. *ASHRAE J.* 43, 26–32.
- Nolan, R., and Weller, W. (2022). Understanding "Stakeholder": A mixed-method approach. *Appl. Psychol.* 71, 425–432. doi: 10.1111/apps.12300
- Park, G. (2017). Acoustic ecology 24. *Contemp. Music Rev.* 36, 175–181. doi: 10.1080/03040467.2017.1356156
- Partridge, J., Joo, S., Yoon, S., and Liu, Q. (2021). Cooling emissions control with IoT sensors and commercial air quality measurements for green and healthy homes. Evaluation of effectiveness and energy consumption. *Energy Build.* 236, 112952. doi: 10.1016/j.enbuild.2021.112952
- Partridge, J., Liu, S., Parker, L., Li, S., Yoon, S., M., and Smith, H. (2019). Forecast CO₂ levels: laboratory measurement of metabolic CO₂ emissions and ventilation and dispersion in a typical office setting. *J. Exposure Prev. Environ. Epidemiol.* 29, 108–117. doi: 10.1038/s41370-019-0171-7
- Partridge, J., and Thers, C. W. (2013). Adequacy of air change rate in the ventilation of an air distribution system's effectiveness to manage airborne disease transmission caused by a rough release in the room with overhead heating radiators: A case study. *HVAC&R Res.* 19, 947–961. doi: 10.1080/10770067.2013.842447
- Pineault, E. (2010). *Hydro-mechanics*. *Trans. Am. Phys. Soc.* 15, 15. doi: 10.1146/annurev-phys-11.02.09.144114
- Pollmann, M., Piccinini, F., Colazzo, S., Cohen, A., and Miani, A. (2020). Indoor air quality at school and students' performance: Recommendations of the UNESCO Chair on Health Education and Sustainable Development & the Italian Society of Environmental Medicine (ISMA). *Health Promotion Perspect.* 10, 109. doi: 10.30172/hpp.2019.29
- Qin, K., and Su, B. (2020). The role of landscape built-rsds for park and the relationship in park cooling effect. *Science* 52, 103864. doi: 10.1016/j.scis.2019.103864
- Rao, M. R., Bortell, C., and Mayer, B. M. (2010). Sampling and preconcentration techniques for determination of volatile organic compounds in air samples. *Anal. Toxicol.* 24, 347–361. doi: 10.1016/j.at.2010.05.009
- Ramos, J., Giraldo-Eggen, F. E., Hernandez, M., Korn, H. E. M., and Kohnmann, A. (2017). The indoor social environment and human task performance: A literature

- room on the role of room acoustics. *Build. Environ.* 123, 305–312. doi: 10.1016/j.buildenv.2017.07.003
- Rhew, V. F., Datta-Laha, V. P., Brown, E. C., Jones, A. D. N., Mathis, P., and Thomas, R. S. (2022). Effect of wearing a face mask on vocal self-perception during a pandemic. *J. Voice* 36, 873–877. doi: 10.1016/j.jvoice.2021.03.008
- Roberts, S. C., Madacki, J., and Schell, B. (2020). Human-vocative communication: current challenges and future prospects. *Philos. Trans. R. Soc. B* 375, 20190254. doi: 10.1098/rstb.2019.0254
- Schmidts, S., Tan, R., Yang, Y., Awa, H., Balachandran, W. R. T., et al. (2022). Indoor air quality and health in schools: A global review for developing the roadmap for the future school environment. *J. Built. Environ.* 17, 10498. doi: 10.1016/j.jbe.2022.10498
- Shan, Z., Yang, Z.-H., Zhou, T., and Chang, Y.-W. C. (2016). Neural signal electroencephalogram (NSE) methods to improve human-building interaction under different indoor air quality. *Energy Build.* 137, 186–193. doi: 10.1016/j.enbuild.2016.05.057
- Sorjonen, A., Pönnä, L., Järvelin, M., and Chao, J. (2021). Airborne transmission: a new paradigm with major implications for infection control and public health. *Nat. Rev. Microbiol.* 19, 1170–1177.
- Sun, S.-L., and Han, J. (2021). How human thermal plumes influence near human dispersion of respiratory droplets and airborne particles: a review. *Environ. Chem. Lett.* 18, 1061–1082. doi: 10.1007/s10311-020-01174-4
- Tan, H., Wong, P. Y., Othman, M. H. D., Kok, H. T., Wajah, R. S., Lim, U. R. P., et al. (2022). Current and potential approaches on assessing indoor air and particle dispersion in healthcare facilities: a systematic review. *Respir. Sci. (publ. for Res. Soc. Open Sci.)* 19, 210470. doi: 10.1093/rsos/190470
- Thom, R. W. (2016). Indoor air quality and its effects on human health: review of challenges and developments in the last 50 years. *Energy Build.* 130, 447–459. doi: 10.1016/j.enbuild.2016.08.071
- Tschentschke, M. A., Gertzeloch, S., Ullrichs, H. J., and Hopfe, P. K. (2017). Review of factors impacting emission/absorption of cooking generated particulate matter. In: *Total Emission*, 186, 1044–1056. doi: 10.1016/j.scitech.2017.02.004
- Toussot, J. C., and Tournier, C. M. (2011). Effects of face masks on speech intelligibility in multi-talker babble noise. *Psych. Sci.* 22, 1026–1032. doi: 10.1177/0956797610389442
- Vinayachandran, R. (2019). Green roofs: A critical review on the role of components, benefits. *Sustainable Environ. Energy Res.* 37, 740–752. doi: 10.1016/j.ses.2019.11.019
- Wang, Z., Ding, W. W., and Singer, R. C. (2010). Performance of low-cost indoor air quality monitors for PM_{2.5} and PM₁₀ from residential sources. *Build. Environ.* 45, 1864–1874. doi: 10.1016/j.buildenv.2010.05.014
- Wang, Z., Poon, S.-H., Li, J. A., Gertzeloch, S., and Balachandran, W. R. T. (2020). The relationships between classroom air quality and children's performance in school. *Build. Environ.* 173, 106740. doi: 10.1016/j.buildenv.2020.106740
- Wells, W. F. (1996). *Antonie van Leeuwenhoek and Air Hygiene: An Ecological Study of Droplet Dispersal* (Cambridge, MA: Harvard University Press).
- Wrightson, K. (2005). An introduction to acoustic ecology. *Soundscapes: J. Acoust. Ecol.* 1, 6–12.
- Wynn, D. P. (2006). The effects of indoor air quality on performance and productivity. *Indoor Air* 16, 347–355. doi: 10.1111/j.1364-3041.2004.00306.x
- Xu, J., Gaudreau, M., Fancello, L., P. de Montigny, J. E., Albert, R., Liu, P., et al. (2020). Infectious virus in ethical tooth clinic symptomatic neonatal influenza cases from a college community. *Proc. Natl. Acad. Sci.* 117, 10941–10946. doi: 10.1073/pnas.1706411119
- Zhao, W., Zhang, K., Xie, J. A., Tian, M., and Burch, J. (2021). Separation process for low "in person" and low "nearby" face. *Integr. Environ. Sci.* 17, 10. doi: 10.1016/j.ienv.2021.100227
- Zong, L., Hu, L., Ai, X., and Huo, M. X. (2022). A review of human thermal plume and its influence on the radiation exposure to particulate matter. *Indoor Build. Environ.* 31, 1754–1774. doi: 10.1177/01431682221090349



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Spatiotemporal variation of alpine gorge watershed landscape patterns via multi-scale metrics and optimal granularity analysis: a case study of Lushui City in Yunnan Province, China

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Introduction: The selection of an optimal scale or granularity in landscape analysis is pivotal for uncovering inherent patterns and changes driven by processes. Variations in spatial resolution can significantly alter the proportions and distributions of various landscape types, thereby impacting the assessment of landscape patterns. Despite its importance, the scale factor is frequently neglected in studies focusing on long-term landscape dynamics.

Methods: Bridging this gap, we utilized remote sensing imagery data from 1986 to 2020 for Lushui City, integrating remote sensing (RS) and geographic information system (GIS) technologies to generate land cover maps. Our focus centered on investigating the sensitivity of landscape pattern indices within the 30–1000 m scale. Combining the first scale domain with an information loss assessment model, we identified the optimal granularity for the analysis, conducting a detailed spatiotemporal examination of landscape pattern from 1986 to 2020 using the index analysis method.

Results and discussion: The results show that: (1) The dominance of forests in Lushui City, yet reveal a significant increase in construction land area over the study period, primarily driven by the conversion of forest and grassland. (2) Among the 10 examined indices, four (FD, ED, TE, and LSI) demonstrated predictable responses to changes in granularity, while three (PAFAC, COHESION, AI) exhibited unpredictable stepwise reactions. Three indices (LPI, SHDI, PLAND) displayed minimal regularity to granularity changes. (3) The optimal long-term landscape analysis granularity for Lushui was identified as 100 m. (4) Before 1996, the city's landscape exhibited characteristics of aggregation, good connectivity, and minimal anthropogenic disturbance. However, post-1996, the landscape experienced disruptions, leading to an overall increase in fragmentation. The expansion of cultivated land and

construction land due to urbanization has intensified landscape fragmentation. However, policies such as converting cropland to forest and planned ecological civilization initiatives have restored forest coverage and improved landscape cohesion and connectivity in Lushui City. This research offers vital insights for ecological planning and resource management in alpine valley watershed cities, deepening our grasp of landscape pattern evolution.

Keywords

spatial granularity, Lushui City, land use, landscape pattern, spatiotemporal changes

1 Introduction

Landscapes are heterogeneous regions comprised of multiple ecosystems or mosaics of different land use type (Sandel et al., 2012), and their patterns have become a crucial focus of ecological research. They are both the concrete manifestation of landscape heterogeneity and the result of various ecological processes operating at different scales (Wagner and Horton, 2000). Diverse landscape types, such as large grasslands, beautiful lakes, and impressive mountains, offer tourism a wide variety of natural resources. Studying landscape patterns and their dynamic evolution processes enables a deeper understanding of the interaction mechanisms between human activities and the natural environment, revealing the distribution characteristics and interrelationships of land resources within a region. This, in turn, provides a scientific basis for land use planning, urban planning, tourism resource development, and more (Gustafson, 1998; Fu et al., 2004; Dainoff et al., 2010). Through landscape pattern analysis, we can identify the factors and mechanisms that generate and control spatial patterns, compare the spatial patterns and effects of different landscapes, and uncover the impacts of landscape changes on landscape services (Yu et al., 2019; Van der Wal et al., 2020; Li et al., 2023). Then serves as a solid theoretical foundation for the scientific planning and development of tourism resources.

Notably, the influence of landscape patterns on ecological processes exhibits a pronounced scale dependence, making scale selection a crucial factor in guiding the scientific exploration of land-use landscape changes and ecological effects in the study area (Zhong et al., 2024). This scale effect is not only pivotal for maintaining ecological balance but also profoundly influences the planning and design of tourism activities, as the diversity, integrity, and accessibility of landscapes exhibit varying degrees of change at different scales, thereby determining the attractiveness and sustainability of tourism resources. Research on the spatial scale of landscape patterns distinguishes between artificially defined boundaries and natural landscape boundaries. Artificially defined

boundaries correspond to various administrative levels, such as global, national, provincial, county, and township scales. In contrast, natural landscape boundaries are represented in features such as watersheds, wetlands, grasslands, and protected areas.

In landscape scale studies, the granularity effect plays a pivotal role. Granularity refers to the smallest identifiable unit in a landscape, usually corresponding to the minimum resolution and size of pixels in spatial data and image materials. It significantly influences the description and analysis results of landscape patterns (Hao and Li, 2001). Previous granularity studies have revealed that observed landscape patterns may differ at different granularities. Smaller granularities can provide more detailed information but may lead to excessive subdivision and increased noise, while larger granularities can simplify the analysis but may overlook some important details (Zhong et al., 2024; Wu et al., 2024; Tang et al., 2024; Feng et al., 2025). Therefore, selecting an appropriate granularity is crucial in landscape pattern research, considering the location and characteristic differences of the study area, as well as the methods, range, and step size of granularity division (Sagardía et al., 2004). Only when the measurement scale, research objectives, and intrinsic features align with the study area can landscape indices accurately display and reflect the landscape patterns of the study area (Fan et al., 2010). However, most studies focus solely on the impact of spatial scale on landscape patterns for a specific period, emphasizing the scale effect of static patterns and paying less attention to the scale effect of dynamic pattern changes. There is a particular lack of research on the spatial granularity effect of land-use pattern changes.

In alpine gorge areas, the complex topography and varied climatic conditions, coupled with the generally steep slopes of arable land, collectively form the natural bottleneck for land use efficiency in such regions (Bao et al., 2011). Additionally, frequent natural disasters such as landslides and debris flows pose a severe threat to ecological safety and the sustainable use of land resources (Chen and Shi, 2014; Huang et al., 2023). Against the backdrop of rapid urbanization, alpine gorge areas are also inevitably profoundly affected by this trend. On one hand, the occupation of surrounding high-quality arable land and ecological land exacerbates the

contradictions and conflicts between different types of land use; on the other hand, indiscriminate expansion strategies further intensify the degree of land fragmentation, posing a serious challenge to regional ecological security (Li, 2022). Concurrently, the implementation of ecological restoration projects such as converting farmland back to forest has played a positive role in mitigating land fragmentation and restoring landscape connectivity (Qi et al., 2021). However, the dynamic balance between destruction and conservation continuously reshapes the landscape pattern. In this context, an in-depth investigation of the dynamic characteristics of multi-scale landscape patterns and their granularity thresholds in alpine gorge areas can enhance our understanding of biodiversity maintenance mechanisms within large-scale geographical contexts and provide vital theoretical support for the development of scientifically sound ecological conservation strategies. Although academic studies have addressed the spatiotemporal variations in landscape patterns in alpine gorge watersheds (Gao et al., 2022; Huang et al., 2022; Wang et al., 2023), there are still many gaps regarding the optimal scale of analysis.

Lushui city is located in the heart of the Nujiang River Basin. The Nujiang River Basin is a region of remarkable heterogeneity and diversity on a global scale, forming high mountains, deep valleys and unique river valley ecosystems. It has various landscape types and rich ecological resources. The dynamic changes in landscape patterns within the basin directly impact crucial ecosystem services such as water conservation and soil retention. As a nationally prioritized ecological functional zone for soil and water conservation, and a testing ground for China's conservation efforts, Lushui holds significant ecological strategic importance. Given Lushui's relatively underdeveloped economic base, urbanization, agricultural expansion, and infrastructure development have pronounced impacts on landscape patterns and their spatio-temporal variations. This makes Lushui a critical area for study. Moreover, the city's diverse ethnic groups and rich cultural heritage lead to varied land use practices that significantly influence landscape patterns and their temporal evolution, warranting in-depth investigation. Therefore, this study focuses on Lushui City to explore the dynamic changes in multi-scale landscape patterns and analyze the optimal spatial resolution required in this complex terrain with sensitive human-nature interactions. Such research is crucial for understanding the interactions between humans and landscapes within large-scale geographical contexts and for developing scientifically informed ecological protection strategies.

This study used long-term land classification data from 1986 to 2022. We selected key landscape pattern indices to analyze the grain effect of landscape patterns at multiple scales. Through fitting function analysis, we explored the grain response characteristics of landscape patterns across different scales and inferred the optimal grain thresholds for each spatial scale. This research provides a foundational understanding and reference for spatial grain selection in subsequent landscape pattern optimization, ecosystem function analysis, forest landscape restoration, and ecological rehabilitation. It also highlights the role and importance of the grain effect in landscape changes.

2 Materials and methods

2.1 Study area

Lushui City (98°09'–99°34'E, 25°33'–26°32'N) is located in Nujiang Prefecture in the northwest of Yunnan, China (Figure 1). With a maximum horizontal extent of 38 km, a vertical span of 108 km, and covering an area of 3203.04 km² (Li et al., 2019), Lushui City experiences an Indian Ocean tropical monsoon climate. Its unique topography creates a three-tier vertical climate, encompassing a river valley subtropical zone, a mountain temperate zone, and a high-altitude frigid zone. Overall, the climate features a small annual temperature difference, significant daily temperature fluctuations, noticeable dry and wet season variations, and indistinct seasonal changes (Li et al., 2021).

Lushui City is located at the core area of the Nujiang River Basin, a crucial high mountain and deep valley topographic region. As a typical high mountain gorge region, approximately 94% of the city's terrain is mountainous, with forests constituting the main land use type. It is designated as a national key ecological function area for soil and water conservation and serves as a pilot base for soil and water conservation efforts in China. The Nujiang River Basin is a region of significant heterogeneity and diversity on a global scale, featuring unique alpine gorge landscapes and river valley ecosystems. The landscape patterns and their dynamic changes within the basin directly impact regional ecosystem services such as water conservation and soil retention. Additionally, these patterns significantly shape the area's biodiversity and the complexity of its ecological processes. With the annual increase in forest coverage in Lushui City, the ecological environment has significantly improved. Lushui City has a population of approximately 200,000 people, primarily composed of Han and various ethnic minorities, with a high proportion of minority populations contributing to its rich cultural diversity. Economically, Lushui City is predominantly agricultural, with key crops including rice, corn, and wheat, alongside significant cultivation of tea, walnuts, and edible fungi as cash crops. In recent years, the development of the tourism industry, particularly eco-tourism centered around high mountain gorges and ethnic culture, has rapidly emerged as a crucial driver of local economic growth.

2.2 Data collection and processing

The research data spans from 1986 to 2022 and comprises Landsat images sourced from the United States Geological Survey (USGS). These images underwent essential preprocessing steps, such as radiometric calibration, atmospheric correction, subset, and mosaicking, to obtain the image data for Lushui City in 1986, 1996, 2004, 2010, 2016, and 2022. The bad tape problem in the Landsat 7 satellite image was fixed with the "landsat_gapfill" plugin in ENVI software. All images were processed using the WGS-1984 coordinate system, and specific details about each image are provided in Table 1.

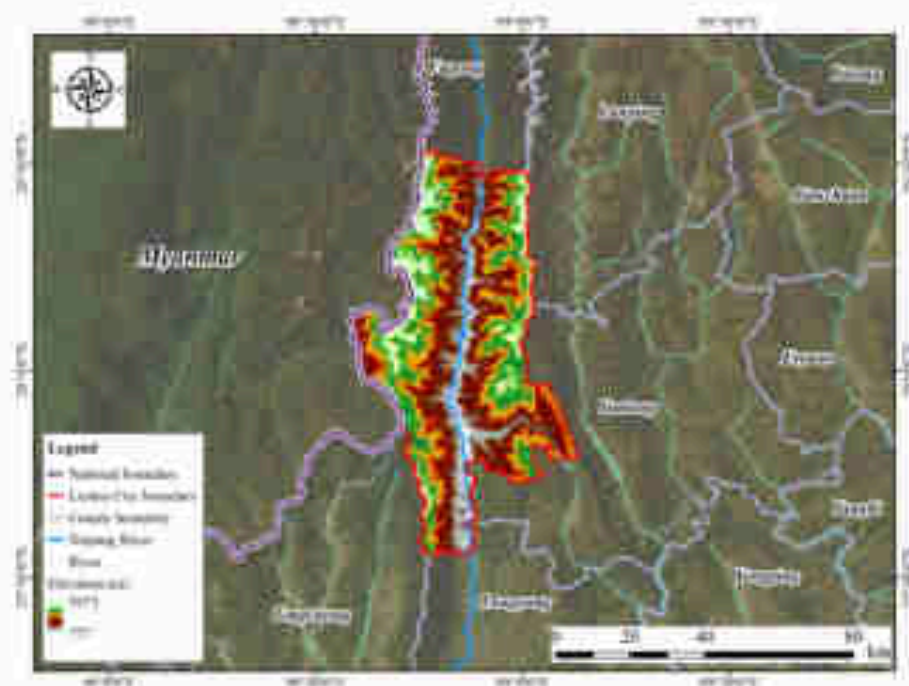


FIGURE 2
Location and the digital elevation model (DEM) of the study area.

Taking into account the current state of the study area and guided by principles of practicality, scientific rigor, and comprehensiveness, the research categorized land use in the study region into five main groups: cultivated land, forest land, grassland, construction land, and water bodies. This classification followed the system provided by the China Academy of Sciences Resource and Environmental Science Data Center for land use remote sensing monitoring.

The widely utilized Maximum Likelihood Classification method was applied in the computer interpretation process, with ground truth data utilized for accuracy verification during the primary classification (Valueres, 2011). To maintain an accuracy level exceeding 80%, a human-machine interactive interpretation mode was employed for visual interpretation and correction.

Utilizing remote sensing and Google Earth historical images, we selected 100 sample points per year in each study area. The ENVI 5.3 software platform was employed for analysis, and accuracy verification was performed using the evaluation module based on

the confusion matrix (Zhang et al., 2017). The results confirm that the Kappa coefficients for various periods exceed 0.8, ensuring an overall accuracy consistently above 85% (Tables A1–A4).

2.3 Landscape pattern indices

This study utilized landscape pattern analysis software to compute landscape indices and analyze the spatial patterns of land use in Linhai City at two levels: landscape and landscape class. At the class-level indexes, the study identified features such as the quantity and spatial configuration of individual patch types. At the landscape level, the main identified features encompassed the spatial patterns of the entire landscape mosaic, including composition and configuration. To comprehensively explore the relationship between various patches in the city and urban development changes in Linhai City, the study selected landscape-level indices, namely Cohesion (COHESION),

TABLE 1 Data source and detailed information.

Image ID	Data source	Imaging time	Sensor	Path-Row	Spatial resolution (m)	Cloud cover (%)
L7T130421981408C01	Landsat5	1986-12-11	TM	112/42	30	11
L7T1304219863703790	Landsat5	1986-12-12	TM	112/42	30	17.63
L7T1304220040398C01	Landsat7	2000-12-29	ETM+	112/42	30	9.67
L4T1304220011018C01	Landsat7	2000-12-15	ETM+	112/42	30	4.3
L8T1304200944022001	Landsat8	2014-12-29	OLI	112/42	30	1.2
L8T1304201311122001	Landsat8	2013-11-29	OLI	112/42	30	0.19

TABLE 2 | Ecological significance of landscape pattern indices.

Type	Landscape pattern indices	Ecological significance
Landscape level	Coarseness (COHESION)	The aggregation and dispersion of patches in the landscape, and its value is in the range of $-1 \sim 1$.
	Shannon's Diversity Index (SHDI)	The heterogeneity within a landscape, providing a measure of ecological complexity and resilience to environmental changes.
	Perimeter-Area Fractal Dimension (PAFRAC)	The non-integer dimension of the irregular geometric shape of the landscape, reflecting the complexity of the landscape shape.
	Edge Density (ED)	A direct response to the degree of landscape fragmentation, and the higher the density of the boundary, the higher the degree of landscape fragmentation.
	Patch Density (PD)	The ratio of patch number to patch area in landscape types.
	Largest Patch Index (LPI)	The area of the largest patch in a landscape in landscape class.
Class level	Percentage of Landscape (PLANL)	Various types of land accounted for the proportion of the total area, the largest area for the main landscape.
	Number of patches (NP)	The number of patches or the number of current types of landscape patches.
	Landscape Shape Index (LSI)	The complexity level of patch shapes.
	Aggregation Index (AI)	Connectivity between landscape-type patches. The smaller the value, the more discrete the landscape.

Shannon's Diversity Index (SHDI), Perimeter-Area Fractal Dimension (PAFRAC), Edge Density (ED), Patch Density (PD), and Largest Patch Index (LPI). At the class level, the study considered four aspects: Percentage of Landscape (PLANL), Landscape Shape Index (LSI), Total Edge (TE), and Aggregation Index (AI). The calculation formulas and significance of landscape pattern indices are presented in the Table 2.

2.4 Spatial grain analysis

2.4.1 First scale domain

This study explores granularity, focusing on the spatial resolution of remote sensing images and the size of the analysis data raster. Using

annual 30m-resolution remote sensing images of Lushui City, the research explores the sensitivity of landscape pattern indices to granularity variations across different spatial resolutions. Landscape classification vector maps were imported, vector data were rasterized, and resampling was conducted through the dominant type method within a granularity range of 30–1000m (Chen et al., 2005). Among the selected 25 granularity sizes, each raster was imported to calculate landscape pattern indices, enabling a comprehensive analysis of the granularity effect in Lushui City. The first scale domain, where landscape indices change with grain size, holds the most landscape feature information. Determined by the first inflection point on the response curve of landscape indices, the first scale domain is the region between the two inflection points (Chen et al., 2007). To ensure efficient data processing and present rich landscape feature information in landscape pattern studies, the spatial granularity slightly larger than the minimum granularity value within the first scale domain should be chosen as the suitable granularity for the study area.

2.4.2 Information loss evaluation model

In the resampling of land-use landscape data to coarser granularity, alterations in the boundaries and perimeters of raster data occur, causing changes in adjacent land class attributes and resulting in the loss of effective information. Hence, in landscape pattern analysis, it is recommended to choose a scale domain with minimal and relatively stable landscape information loss. To quantify the information loss for different landscape classes during data resampling, the absolute values of landscape information losses are summed (Zhai et al., 2019). Following this principle, the information loss evaluation model is expressed as follows:

$$P = \left| 100 - \frac{M}{A_b} \right| \quad (1)$$

$$M = \sum_{i=1}^n |A_{ip} - A_{bi}| \quad (2)$$

where: P represents the percentage of information loss for a specific landscape pattern index; M is the total amount of information loss for that landscape pattern index; A_b is the sum of baseline data values (30m) for all landscape types; A_{ip} is the corresponding raster data value for the i th landscape type for that index; A_{bi} is the baseline data value (30m) for the i th landscape type for that index; n is the total number of land-use landscape types.

3 Results

3.1 Land use changes in Lushui City from 1986 to 2022

3.1.1 Changes in land use structure

According to Table 1, the land use structure changes in Lushui City from 1986 to 2022 exhibit the following characteristics: (1) Cultivated land has shown an overall increase, expanding its proportion from 11.75% to 28.25% of the total area. Forest, a major land use type in Lushui City, has decreased from 2169.25

TABLE 3 | Land use structure in Lushui City from 1996 to 2022.

	Cultivated land		Forest		Extraction		Construction land		Wetland	
	Area	Percentage (%)	Area	Percentage (%)	Area	Percentage (%)	Area	Percentage (%)	Area	Percentage (%)
1996	961.29	11.71	2,169.29	75.16	116.68	16.72	27.25	0.88	12.19	0.46
1998	969.62	11.58	2,266.77	71.29	862.99	11.34	35.44	1.13	9.34	0.30
2004	473.87	13.39	3,339.76	66.11	426.95	13.75	43.83	2.39	2.90	0.29
2010	909.17	18.70	1,810.71	61.37	306.34	16.43	66.76	3.61	8.25	0.27
2016	478.35	15.47	2,087.86	67.34	654.72	14.79	61.81	1.99	6.13	0.30
2022	623.96	18.25	1,896.79	61.11	104.17	11.75	102.96	1.21	11.88	0.18

km² to 1956.79 km². However, during the periods 1996–1998 and 2010–2016, forest increased, possibly due to afforestation projects. (2) Grassland area declined from 1996 to 1998, rose an increase from 1998 to 2010, and then decreased again, constituting approximately 14% overall. (3) Construction land witnessed a significant increase, growing from 27.25 km² in 1996 to 102.30 km² in 2022, reflecting urbanization characteristics. (4) The overall proportion of water bodies is relatively low, exhibiting a decrease followed by an increase during the study period.

3.1.2 Land use transfer characteristics

Between 1996 and 2022, Lushui City witnessed frequent transitions among different land use types, primarily due to significant conversions involving forest land, cultivated land, and grassland (Figure 5). During the periods 1996–2004, 2004–2010, and 2010–2022, forest converted to cultivated land by 196.85 km², 170.89 km², and 159.39 km², respectively. In the years 2016–2022, construction land underwent rapid expansion, predominantly transitioning from forest (27.99 km²) and cultivated land (25.25 km²). This phase marked an accelerated urbanization process, characterized by a development pattern focused on incremental land use, resulting in extensive expansion of the central urban area and substantial encroachment of construction land into cultivated land and other land types.

3.2 The spatiotemporal scale effect of landscape pattern indices

3.2.1 Scale effect of landscape-level landscape pattern indices

Changes in landscape granularity can modify patch boundaries, segmentation, or fusion, thereby altering landscape patterns and leading to corresponding adjustments in the indices used to characterize these patterns.

At the temporal scale, discerning the consistency of landscape index response curves across six periods allows for the classification of indices into three types. Type I exhibits predictable responses to scale changes, exemplified by PD and ED. Type II demonstrates step-like responses that are less predictable, like PAFLAC and

COHESION. Type III displays instability and lacks consistent scale relationships during scale changes, typified by LPI and SHDI.

From Figure 5, it is evident that both PD and ED in Lushui City's land use landscapes follow a decreasing "U" trend as granularity increases, displaying a strong fit with power functions, with R² exceeding 0.96 (Table A7). This highlights the high predictability of these indices, facilitating accurate extrapolation or interpolation of landscape features at various spatial scales. PD notably declines as granularity increases, particularly before reaching 100m, with a lesser decrease between 100–200m, and stabilization occurring after 200m, with minimal granularity-induced fluctuations. Similarly, ED experiences rapid decreases within the 10–100m granularity range, followed by gradual flattening beyond 300m. This trend suggests that as granularity rises, smaller patches within the landscape merge gradually with dominant ones, thereby reducing landscape fragmentation, promoting a more uniform landscape shape, and enhancing the dispersion of different land use types. The consistency in PD and ED variations across different periods indicates that the scale effects of these two indices remain unaffected by time.

Type II PAFLAC demonstrates a step-like increase with increasing granularity, with the first inflection point occurring between 60–100m. At a granularity of 100m, it undergoes a gradual increase across all years, albeit with slight variations. Before 200m, the most significant growth occurred in 2016, while after 250m, the increase peaked in 1998, with 2016 showing the most fluctuation between 400m–800m. In contrast, COHESION exhibits a step-like decrease with increasing granularity, with more pronounced changes at smaller scales. The first inflection point for Patch Cohesion ranges from 40–110m across different years, with notable fluctuations observed in 2022.

Type III LSI shows varying ranges of the first inflection point, spanning from 40–450m across different years. Unlike other indices, the inflection points for Landscape Shape Index are relatively broad and shift over time, with the first inflection point occurring at 450m in 2022. This suggests significant variability in the response of Landscape Shape Index to granularity across different periods. SHDI displays the first inflection point ranging from 120m to 225m in different years.

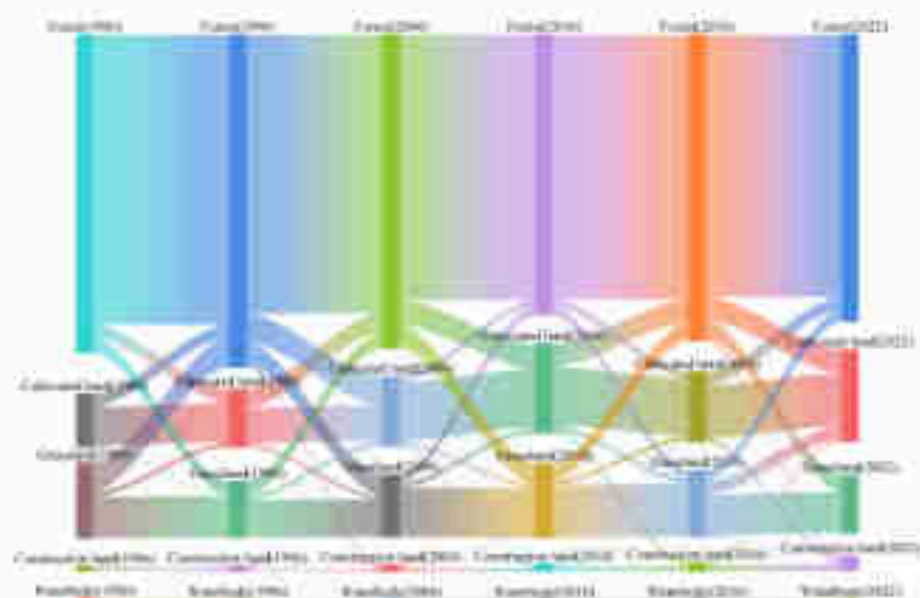


FIGURE 2
Land type transition map.

3.2.2 Scale effects of class-level landscape pattern indices

At the class level (Figure 3), PLAND exhibits irregular changes with increasing granularity. Generally, PLAND for grassland, forest land, cultivated land, construction land, and water bodies shows minimal variation with granularity before 100m, followed by increased fluctuations after 100m. PLAND responses to scale

differ across different years. TP and LSI decrease with increasing granularity for all five land types, following predictable power curves for grassland, cultivated land, forest land, and construction land, with significant reductions in variance after a granularity of 100m and a flattening trend after 200m. Comparatively, despite varying initial granularity values (30m) for these land types across different years, their responses to granularity exhibit consistent

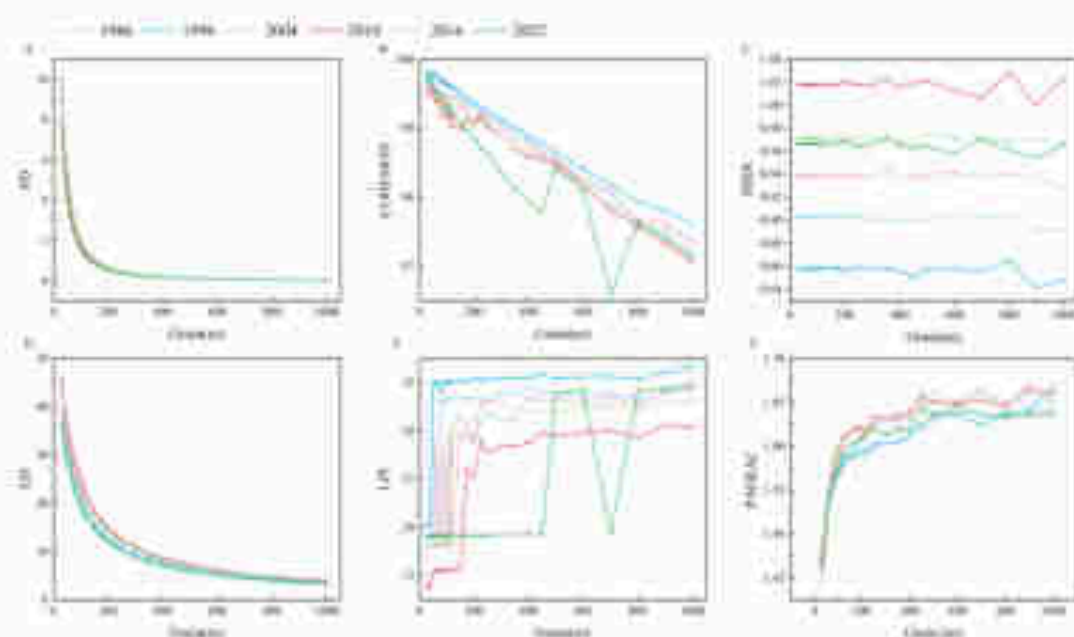


FIGURE 3
Landscape-level landscape pattern response curves: (a) Patch Density (PD); (b) Landscape Index (LI); (c) Shannon's Diversity Index (SHDI); (d) Edge Density (ED); (e) Largest Patch Index (LPI); (f) Perimeter Area Ratio (PAR). Granularity: 0-1000m.

trends and magnitudes over time, indicating that the scale response of these indices is not influenced by time. The TE of water bodies shows a step-like decreasing trend with increasing granularity, with most years exhibiting an inflection point around 120m, while the first inflection point for water body LSI ranges from 60–120m, reflecting the sensitivity of edge indicators for this land type to scale changes compared to others. AI shows a two-stage response to scale, with slight variations between different land types. Grassland, cultivated land, and forest land exhibit a significant decline before 200m, followed by a slowing trend after 200m, with a few inflection points. Construction land and water bodies enter a stable period around 100m, with both frequency and magnitude of index changes increasing with scale. The variations in these indices for different land types also differ across different years.

3.3 Determination of suitable granularity for landscape pattern analysis

3.3.1 First scale domain

By employing the first scale domain method to analyze the granularity response curves of landscape-level indices in Lushui City across different years, we found consistent scale inflection points for the chosen six indices at 100m and 200m. Similarly, through an examination of the granularity response curves of class-level indices across various land use types, we determined the first scale domain and appropriate granularity range for each index, as detailed in Table 4. The first scale domain is categorized into two ranges: 30–100m and 30–200m. Consequently, we conclude that the optimal scale for landscape pattern analysis in Lushui City is 100m.

TABLE 4 The first scale domain of each index.

	Landscape pattern indices	The range of the first inflection point	The suitable granularity range
Landscape level	PD	100m	30–100m
	ED	100m	30–100m
	PAFRAC	60–100m	30–100m
	COHESION	60–100m	30–100m
	LPI	40–100m	30–100m
	SHDI	100–200m	30–200m
Class level	PLAND	100m	30–100
	TE	100–120m	30–120m
	LI	60–120m	30–120m
	AI	100–200m	30–200m
Total			100m

3.3.2 Information loss evaluation model

This study investigated the impact of granularity on the landscape information loss of 10 landscape pattern indices in Lushui City from 1986 to 2022, as illustrated in Figure 5. Generally, the information loss of each index increases with granularity, but they display diverse trends. Indices like PD, ED, TE, and LSI witness rapid information loss as scale increases. PD and LSI stabilize after 300m, while ED and TE plateau after 400m. Thus, a narrower scale range is preferable for these indices. PAFRAC and AI show fluctuating information loss with scale, with the first inflection point typically around 100m, followed by stable fluctuations after 450m. Across different years, COHESION, SHDI, and PLAND exhibit minor fluctuations within the initial 100m range but experience rapid information loss thereafter. The information loss curves of LPI vary notably among different years, with most indicating the first inflection point around 100m. Overall, all landscape indices demonstrate relatively stable changes and minimal information loss around 100m. Based on the analysis of the information loss evaluation model, the suitable granularity range for landscape pattern analysis is determined to be 100m.

3.4 The spatiotemporal variation of landscape pattern indices in Lushui City

3.4.1 The spatiotemporal variation of landscape pattern indices at the landscape level

We selected a granularity of 100 meters as the most suitable scale for analyzing landscape pattern changes in Lushui City. Consequently, we conducted a spatiotemporal analysis of landscape pattern indices for six periods using a granularity of 100 meters. The analysis results of six landscape indices at the landscape level, including PD, ED, PAFRAC, COHESION, LPI, and SHDI, in the study area are shown in Figure 6.

PAFRAC shows overall stability, peaking at 1.60 in 2010, reflecting the most intricate landscape shapes during that period. Similarly, ED reached its peak in 2010, indicating significant landscape fragmentation in Lushui City. PD fluctuated between 1.54 and 1.99, with an initial decline, subsequent increase, and another decline. PD steadily rose from 1996 to 2010, hitting a peak of 1.991 in 2010. SHDI declined from 1986 to 1996, then rose to a peak of 1.019 in 2010 before gradually decreasing. COHESION and LPI followed similar trends from 1986 to 2022, peaking before 1996, declining steadily until 2010, and then experiencing a slight increase. These trends suggest reduced human impact on the landscape before 1996, increasing interference thereafter, and some improvement post-2010.

In summary, Lushui City's landscape exhibited a high level of cohesion and connectivity before 1996, with minimal human interference. However, after 1996, the landscape began to degrade, showing increased fragmentation, reaching its peak in 2010, before gradually recovering. This shift could be attributed to the city's urban development trajectory. Following 1996, the

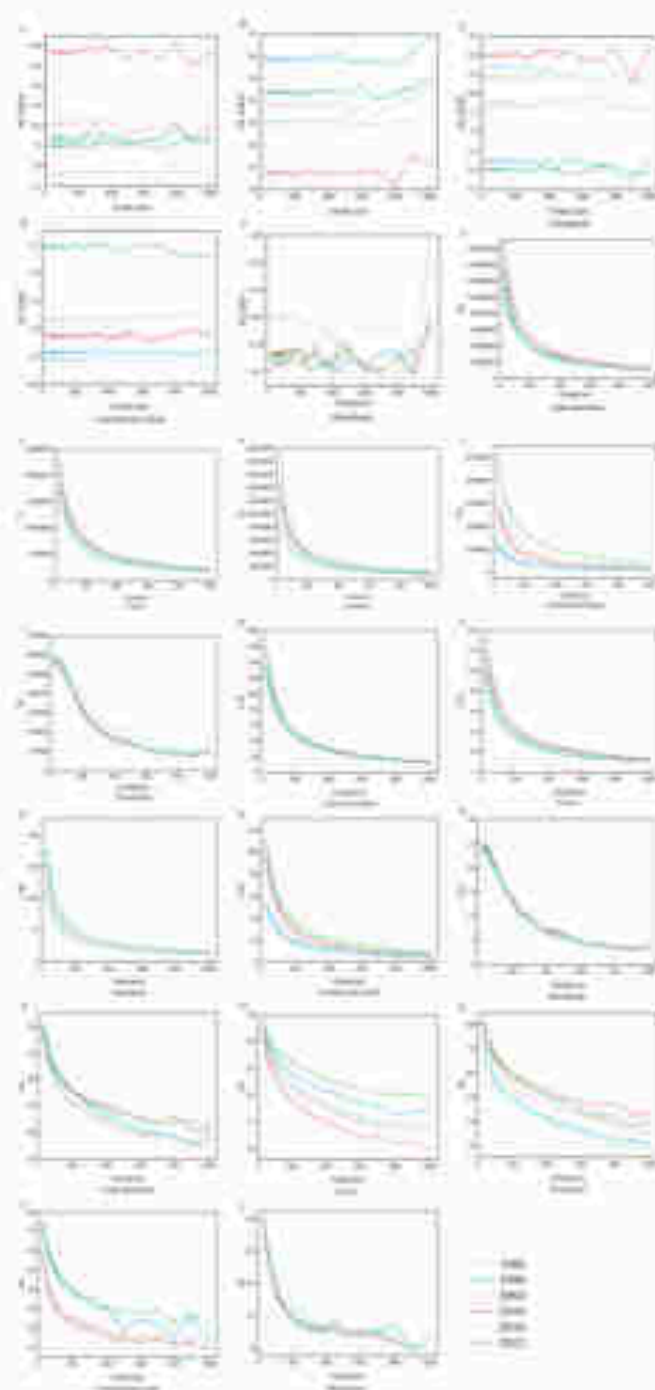


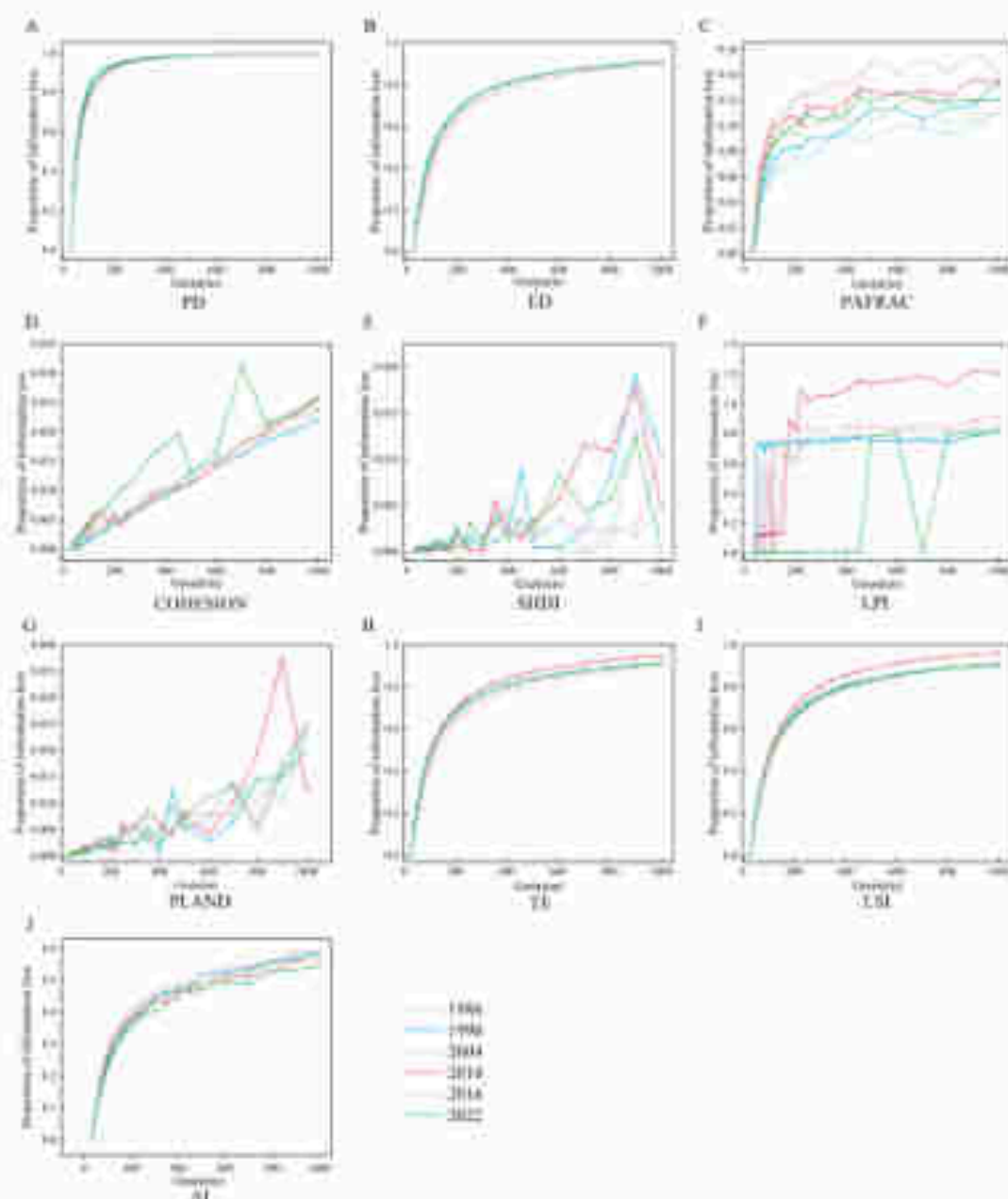
FIGURE 4

Horizontal ecological diversity indices: (A) PLAND: Cultivated land, (B) PLAD: Forest, (C) PLSD: Grassland, (D) PLBD: Construction land, (E) PLGD: Waterbody, (F) PLHD: Cultivated land, (G) PLMD: Forest, (H) PLSD: Grassland, (I) PLBD: Construction land, (J) PLGD: Waterbody, (K) PLHD: Cultivated land, (L) PLMD: Forest, (M) PLSD: Grassland, (N) PLBD: Construction land, (O) PLGD: Waterbody, (P) PLHD: Cultivated land, (Q) PLMD: Forest, (R) PLSD: Grassland, (S) PLBD: Construction land, (T) PLGD: Waterbody, (U) PLHD: Cultivated land, (V) PLMD: Forest, (W) PLSD: Grassland, (X) PLBD: Construction land, (Y) PLGD: Waterbody, (Z) PLHD: Cultivated land, (A) PLMD: Forest, (B) PLSD: Grassland, (C) PLBD: Construction land, (D) PLGD: Waterbody, (E) PLHD: Cultivated land, (F) PLMD: Forest, (G) PLSD: Grassland, (H) PLBD: Construction land, (I) PLGD: Waterbody, (J) PLHD: Cultivated land, (K) PLMD: Forest, (L) PLSD: Grassland, (M) PLBD: Construction land, (N) PLGD: Waterbody, (O) PLHD: Cultivated land, (P) PLMD: Forest, (Q) PLSD: Grassland, (R) PLBD: Construction land, (S) PLGD: Waterbody, (T) PLHD: Cultivated land, (U) PLMD: Forest, (V) PLSD: Grassland, (W) PLBD: Construction land, (X) PLGD: Waterbody, (Y) PLHD: Cultivated land, (Z) PLMD: Forest.

economy underwent rapid growth, accelerating urbanization and causing ongoing destruction and encroachment on natural landscapes. However, after 2016, the construction of ecological civilization was incorporated into the five-in-one overall layout of socialism with Chinese characteristics. Lushui City has deeply implemented this initiative, commencing vigorous efforts to protect the environment, leading to the restoration of landscapes.

3.4.2 The spatiotemporal variation of landscape pattern indices at the class level

The characteristics of different landscape types vary significantly (see Figure 7). Forest consistently dominates Lushui City's landscape, having the highest PLAND values, followed by cultivated land and grassland, whereas construction land and water bodies exhibit lower PLAND values. Forest and cultivated



FIGURE

Response of landscape pattern metrics for different grain sizes. (A) PD, (B) ED, (C) PAFRAC, (D) CORCON, (E) SIDI, (F) LPI, (G) PLAND, (H) TI, (I) LSI, (J) AI.

land both peaked in TI values in 2010, while grassland reached its maximum in 1986. Regarding LSI, grassland and cultivated land have relatively larger indices, indicating more irregular patch shapes in these two land types. Water bodies consistently have the smallest and relatively stable LSI values over different years, suggesting relatively simple patch shapes. Conversely, there is an increasing trend in construction land's LSI, indicating a gradual shift towards irregular patch shapes in this land type. Forest and cultivated land show relatively stable changes in AI from 1986 to 2022, while grassland shows a trend of gradual enhancement, indicating strong spatial aggregation. Construction land and water bodies fluctuate over different years, primarily due to their

susceptibility to human disturbance, leading to instability in their aggregation levels.

4 Discussion

4.1 Response of landscape metrics to changing grain size

This study examines variations in landscape indices across multiple grain sizes, encompassing both landscape and class levels, to provide a comprehensive portrayal of analyzed

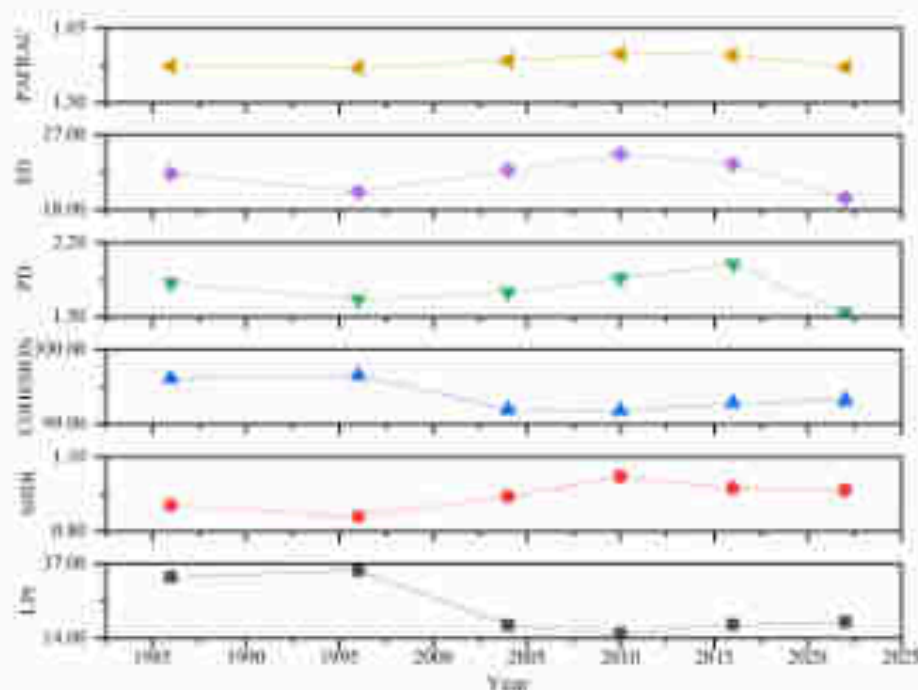


FIGURE 2

Temporal variation of landscape metrics at the landscape level in Lushui City.

landscapes. We selected 10 commonly used landscape indices, including six at the landscape level and four at the class level. Notably, indices such as PD and ED at the landscape level, and LSI and TE at the class level, decreased as grain size increased. This trend is attributed to patch fusion with larger grain sizes, reducing patch numbers, weakening boundary effects, and decreasing shape indices. Conversely, indices like COHESION at the landscape level and AI at the class level showed a stepped downward trend due to enlarged grain sizes blurring patch boundaries and merging smaller patches. This disrupts landscape connectivity, reducing overall cohesion and aggregation. Larger grain sizes also tend to homogenize landscape appearance, potentially dispersing patch type distributions and further lowering COHESION and AI values. Furthermore, changes in grain size influence patch type dominance, potentially reducing landscape diversity and homogenizing aggregation areas. This observation aligns with findings by Zhang et al. (Zhang et al., 2010). On the other hand, PAFRAC exhibited a stepped upward trend with increasing grain size, consistent with Qian et al.'s findings (Qian et al., 2022), validating our results. LPI and SHDI at the landscape level, as well as PLAND at the class level, did not exhibit regular changes with scale variations. This aligns with observations of landscape granularity effects in coastal wetlands by Peng et al. in Yancheng (Tian et al., 2014). LPI increased with grain size due to patch merging up to a certain threshold, beyond which the largest patch stabilized, fluctuating within a specific range. The inconsistent scale relationship for indices like SHDI and PLAND may be due to

Lushui City's dominance by forest landscapes, comprising over 60% of the area, which minimizes the impact of grain size changes on landscape diversity and class proportions.

Due to the nonlinear ecological processes and interactions within landscapes, the changes in landscape-pattern indices may exhibit different forms with increasing scale (Li et al., 2022). Auto-correlation within landscapes, characterized by similar structures across spatial scales, may lead to power-law curve changes in some indices (Li et al., 2022). However, the inherent diversity and heterogeneity within landscapes can result in irregular or unpredictable trends in response to scale changes, influenced by factors like terrain, land use, and natural environment variations across regions (Wu et al., 2000).

This study combines qualitative and quantitative methods to determine the optimal landscape analysis granularity for Lushui City, pinpointing it at 100 meters. These methods have been extensively validated in other regions like Ganyang, Chongqing, and Shanghai (Wang et al., 2021; Qian et al., 2022; Hu et al., 2023). Despite a slightly larger optimal granularity compared to previous studies within a similar area range, this variation is attributed to differences in regional landscape dynamics and characteristics (Gao et al., 2018; Wang and Li, 2021). Notably, Lushui City's landscape is predominantly forested, with forest landscapes showing lower sensitivity to scale changes compared to other land types. Moreover, our long-term analysis of landscape indices considers variations across different time points, justifying the selection of a slightly larger optimal granularity than that of a single time series.

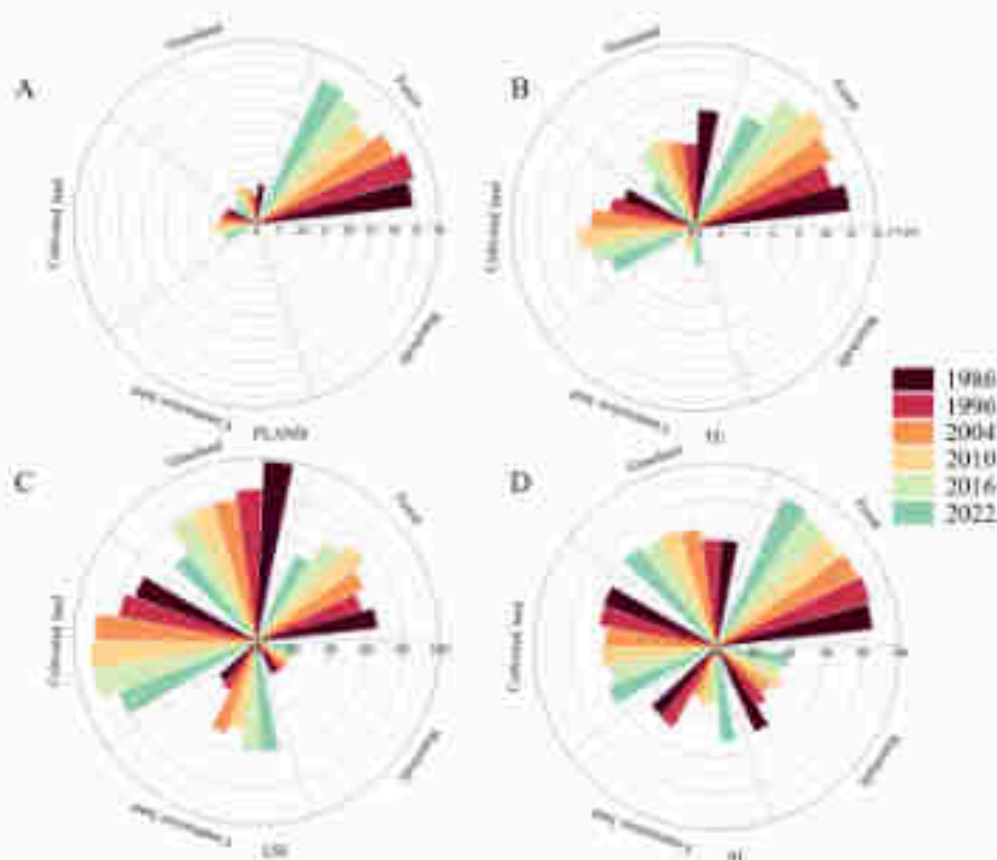


FIGURE 2
Spatial heterogeneity of landscape pattern in the study period (Lushui City, 2016, 2022, 2010, 2004, 1996, 1986).

4.2 Patterns of landscape pattern changes

The changes in land use are easily driven by multiple factors. Land use changes in Lushui City are closely related to local policies. The main land use type in Lushui City is forestland. During the study period, land use transitions primarily occurred among forestland, cultivated land, and grassland. From 1986 to 2010, the area of cultivated land increased. This was because during this period, Lushui City's economy was predominantly agricultural, directly promoting the expansion of agricultural land in the region. From 2010 to 2016, there was an increase in forestland area while cultivated land area decreased. During this period, Lushui City responded to the national policy of Grain for Green Program by initiating reforestation projects (Li et al., 2021). From 2016 to 2022, Lushui City actively responded to the national call for poverty alleviation and, as one of the deeply impoverished areas, implemented large-scale territorial spatial transformation actions. In this series of measures, the advancement of projects such as relocation and road construction directly led to a sharp increase in construction land area (Li, 2022). While accelerating urbanization, Lushui City also closely followed the national guidelines for protecting cultivated land, making the protection and construction of high-standard farmland a major task (Yang et al.,

2022). Consequently, cultivated land area was restored during this period.

The changes in land use types are the main reason for the transformation of landscape patterns, and quantitatively studying the evolution of landscape patterns is a necessary process to understand the consequences of land use changes (Nie et al., 2022; Ma et al., 2023). Among the selected indicators, PAFLAC, ED, and SHDI show consistent trends: they decreased from 1986 to 1996, increased from 1996 to 2004, and then continued to decrease. In contrast, COHESION and LPI changed oppositely. It can be inferred that Lushui City experienced two significant turning points in landscape pattern changes, namely in 1996 and 2010. In 1996, COHESION and LPI reached their highest values, indicating good connectivity and clustering of species in the landscape, suggesting minimal human interference in Lushui City's landscape before this time (Yang et al., 2021). From 1996 to 2010, PAFLAC, ED, and SHDI increased, indicating increased complexity in landscape patch shapes, fragmentation, and heterogeneity, often associated with human activities such as land development and urbanization processes. The unreasonable expansion of urbanization led to continuous natural patches becoming discontinuous patches (Jiao et al., 2022), resulting in landscape degradation and increased overall fragmentation after 1996. After 2010, urban development

in Lushui City entered a planning phase. While advancing urbanization, the city also emphasized ecological civilization construction, and vegetation restoration not only changed the composition and spatial structure of the landscape types but also improved regional ecosystem functions (Huang et al., 2022).

Urbanization drives modernization and economic growth, propelling regional economic and social advancement. Yet, it also triggers swift alterations in landscape dynamics (Huang et al., 2021).

4.3 Uncertainty

This study offers insights into the long-term landscape analysis scale in Lushui City. However, due to data limitations and real-world constraints, uncertainties persist. Initially, Landsat satellite images with a 30-meter resolution were utilized, and land classification was performed through visual interpretation, posing challenges in ensuring classification accuracy. Nonetheless, the accuracy of land use classification significantly influences the sensitivity of landscape indices (Liu et al., 2011). Lower spatial resolution images may compress or merge individual features, thereby affecting the calculation of landscape pattern indices. For instance, in sparsely populated urban areas, a 30-meter resolution may lead to four times as many buildings compared to a 15-meter resolution (Bhaskar et al., 2003). Therefore, future studies could employ higher resolution images, such as 10m or 5m, coupled with field detection points to enhance land classification accuracy. However, it's crucial to acknowledge that while high spatial resolution images enhance interpretability, they may generate numerous patches, posing challenges during classification algorithm application. Moreover, heightened heterogeneity in high-resolution images significantly impacts spatial correlation and heterogeneity analysis.

In terms of indicator selection, although the landscape pattern indices used in this study provide information about landscape organization, form, connectivity, and diversity, which can describe and quantify the spatial structure and pattern characteristics of landscapes for analyzing the scale response of landscape features, they have overlooked the interaction relationships between landscape patches. These relationships, known as topological indices (Zhang et al., 2024), have been proven to have significant impacts on landscape connectivity and ecological service functions. Future research incorporating topological indices will help in understanding the variations in landscape ecological processes at different scales.

This study focuses on Lushui City as a representative area of alpine gorge watershed, deeply analyzing how land use changes trigger significant changes in landscape patterns across temporal and spatial dimensions. However, it is worth noting that although the research has touched upon the surface changes in landscape patterns, it has not yet conducted a thorough and systematic quantitative analysis of the core factors driving these changes. Existing research has clearly indicated that hydrological processes, climatic conditions, and extensive human activities all act as key drivers that can profoundly impact landscape patterns (Yang et al.,

2022a; Kiewings et al., 2021; Xiong et al., 2023). These drivers, each independently and interwoven with others, collectively shape the evolutionary trajectory of regional landscapes.

In light of this, future research should strive to fill these gaps by constructing scientifically sound quantitative models and indicator systems to conduct in-depth analyses of the driving factors behind landscape patterns. This effort will not only help us better understand the internal logic and external manifestations of landscape evolution in high mountain gorge areas but also provide robust scientific foundations and data support for regional ecological conservation, land use planning, and sustainable development strategies.

5 Conclusion

This study, conducted using remote sensing images spanning from 1986 to 2022, employed the first scale domain and an information loss model to determine the optimal granularity for long-term landscape analysis. It also examined the spatiotemporal changes of landscape pattern indices. The key findings are summarized as follows:

1. The primary land type in Lushui City is forest. During the agricultural dominance period (1986–2010), cultivated land increased. Following the implementation of the policy to Grain for Green Program (2010–2016), forest expanded while cultivated land decreased. During the high-speed urbanization phase from 2016 to 2022, the area of construction land sharply increased. However, concurrently, policies to protect cultivated land contributed to a partial recovery in cultivated land area. The land changes in Lushui City have been significantly influenced by policies.
2. Due to the increased grain size leading to patch fusion and weakened boundary effects, four indicators (PI, ED, TE, and LS) show a predictable “U” shaped decreasing trend with grain size variation, largely unaffected by time. The homogenization and singularization of landscapes caused by larger grain sizes result in two indicators (CH450KN, AI) exhibiting a stair-like declining trend, while PAFRAC shows a stair-like upward trend, with lower predictability and slight differences across different temporal scales. Three indicators (LPI, MHD, PLANI) show no discernible pattern with grain size changes. Therefore, when conducting landscape pattern analysis, priority may be given to selecting indicators that demonstrate predictability.
3. The suitable granularity of the index selected in this study is between 30–200m, with variations observed across different years. In 2022, landscape indices showed a more pronounced response to scale changes. At the class level, water bodies in Lushui City are the most sensitive to scale effects. Combining with an information loss model, conducting long-term landscape analysis of Lushui City at a 100-meter scale is most suitable, as it reduces data

volume while maintaining a relatively low amount of information loss. Landscape indices exhibit significant scale effects. Choosing appropriate scales and landscape indices facilitates further analysis of landscape patterns.

4. This study, based on landscape pattern indices such as PAFRAC, ED, SHDI, COHESION, and LPI, reveals two critical turning points in the landscape pattern changes in Lushui City, 1996 and 2010. Before 1996, landscape connectivity and clustering were relatively high. From 1996 to 2010, with increasing human activities, landscape fragmentation intensified, and heterogeneity increased. However, since 2010, urban development has entered a planning phase, focusing on ecological civilization construction, which has improved ecosystem functions. The damage to Lushui City's landscape due to urban construction and land changes has been somewhat restored after reasonable planning and ecological conservation efforts.

In essence, this study sheds light on effective land management and ecological conservation strategies in Lushui City through a thorough examination of landscape pattern indices and scale effects over an extensive time frame. It furnishes a logical foundation for harmonizing ecological preservation with sustainable development.

Data availability statement

Publicly available datasets were analyzed in this study. The data sources and access links are indicated in the text. Requests to access these datasets should be directed to 20230025@jpm.edu.cn.

References

- Bao, H., Ding, Y., and Li, Y. (2015). Study on ecological evolution mode in alpine valley area—a case study of Lushui county of Yunnan, China. *For. Resour. Manage.* 6, 103. doi: 10.1360/j15c0103
- Burns, B., Jansen, A., and Burslem, D. (2010). Urban spread environmental data: online sensing data. *Appl. Geogr.* 30, 731–740. doi: 10.1016/j.apgeog.2010.02.002
- Chen, X., and Hu, S. (2019). Geospatial landscape division and landscape evolution in the mid-western sector of the Hengduan Mountains, western Qinghai Tibet Plateau. *J. Ar. Sci.* 15, 464–477. doi: 10.1087/j1502-0177-4529-2
- Dederinger, H., Aulic, F., and Mghadheh, M. (2019). Land use change, urbanization and change in landscape pattern in a metropolitan area. *Sci. Total Environ.* 685, 707–719. doi: 10.1016/j.scitotenv.2019.11.207
- Feng, S., Zhao, Y., Han, L., and Ma, C. (2017). Analysis of landscape patterns (I) and values in China, based on grain size effect. *Environ. Monit.* 9, 2261. doi: 10.13868/j.issn.1674-6185.2017.05.001
- Fu, B., Chen, L., Ma, K., and Wang, Y. (2011). *Theory and application of landscape ecology* (Shenyang: China Science Press).
- Guan, D., Jiang, Y., and Chang, L. (2022). Perceive the landscape ecological security pattern be quantitatively optimized and effectively evaluated? An integrated analysis with the granularity metric method and landscape coherence. *Environ. Sci. Pollut. Res.* 29, 4159–4184. doi: 10.1007/s11356-021-16739-1
- Gustafson, E. J. (1990). Quantifying landscape spatial pattern: what is the state of the art? *Environ. Ecol.* 14, 141–154. doi: 10.1007/BF02294620
- Hong, T., Tu, H., Mao, Z., and Zhang, S. (2021). Government-driven urbanization and its impact on regional economic growth in China Cities [17, 103249]. doi: 10.1016/j.jbus.2021.103249
- Hu, C., Wu, W., Zhou, S., and Wang, Z. (2023). Alpine landscape changes in landscape patterns in karst mountainous regions based on the optimal landscape scale: A case study of Guiyang city in karst region, China. *Ecol. Indic.* 150, 110211. doi: 10.1016/j.ecolind.2022.110211
- Jiang, J., Xu, H., Shao, S., Li, A., and Wang, P. (2010). Activity patterns and contributing factors of alpine trees in the Upper Salween Alpine Valley. *Acta Oecol.* 31, 1367–1381. doi: 10.1007/s10044-010-9439-z
- Jiang, K., Peng, L., Wang, X., and Chen, T. (2022). Integrating landscape connectivity and natural-anthropogenic interactions to understand karst vegetation restoration: A case study of guizhou province, China. *Front. Ecol. Evol.* 10. doi: 10.3389/fecv.2022.844407
- Jiang, X., Yu, Y., Zhang, Z., Yu, J., Guo, J., Bogdanovich, M., et al. (2021). A comprehensive assessment of karst fragmentation using morphological-spatial pattern analysis in Qinghai, Western Provinces, China. *J. Ar. Sci.* 18, 2125–2135. doi: 10.1007/s10268-021-0751-0
- Li, Y., Hu, X., Wang, X., Wang, H. X., and Duan, L. (2022). Plant response to global climate change and urbanization: Implications for sustainable urban landscape. *Urbanization* 9, 1022. doi: 10.3389/urban.2022.888222
- Li, Y., Zhou, J., and Fan, W. (2023). Recurrence effects of landscape patterns on ecosystem services at multiple scales based on gradient boosting decision tree models. *Ecology Indic.* 147, 108116. doi: 10.1016/j.ecolind.2023.108116
- Li, X., Yang, M., Brown, A., Xu, H., Niu, T., and Gao, J. (2020). Driving factors and future prediction of land use and cover change based on satellite remote sensing data by the LSTM model: a case study from guizhou province, China. *Sensors* 20, 2771. doi: 10.3390/s20102771
- Li, Q., Jia, T., Peng, Q., Liu, J., Zhang, H., Huang, J., et al. (2022). Identifying the extent of the spatial expression of landscape fragmentation based on scale effect analysis in southwest China. *Ecol. Indic.* 142, 108120. doi: 10.1016/j.ecolind.2022.108120

Author contributions

YW: Conceptualization, Writing – original draft. XY: Formal analysis, Writing – review & editing. QF: Data curation, Writing – review & editing. LW: Visualization, Writing – review & editing. DC: Writing – review & editing. ZT: Methodology, Writing – review & editing.

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Conflict of interest

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- Li, Y. (2022). *Research on Spatial-Temporal Evolution and Optimization of Terrestrial Space in Lushui Based on "Three types of space"* (Wuxi: China Tourism University).
- Li, Y., Wang, D., Yang, J., and Li, X. (2022). Review on the evaluation of ecological environment quality in inland city under the influence of the construction of completed in Great project. *Environ. Sci. Total Environ. Commun.* 28, 266–274. doi: 10.1007/s11368-022-04008-0
- Li, Y., Xu, F., Liu, X., Duan, Y., and Liu, J. (2019). Ecological security evaluation of Lushui County based on GIS. *Environ. Sci. Total Environ.* 56, 36–42. doi: 10.1007/s11368-018-0412-4
- Liang, J., Lin, Y., Ning, L., Li, P., Xu, Y., and Shen, Z. (2014). Road impacts on spatial patterns of land use and landscape fragmentation in three parallel rivers region, Yunnan Province, China. *Chin. Geogr. Sci.* 24, 15–27. doi: 10.1007/s11464-013-0522-y
- Liu, H., Huang, H., Zhou, Q., Guo, S., Li, K., and Fan, Z. (2021). The influence of urban form on surface urban heat island and its planning implications: evidence from 1288 urban districts in China. *Sustainable Cities Soc.* 71, 102987. doi: 10.1016/j.scs.2021.102987
- Liu, Y., Wang, X., Zhou, X., Hu, C., and Li, J. (2022). Spatial-temporal heterogeneity of urban landscape changes in the built-up areas around the city of southwest China: a case study in central urban area of Guiyang city. *Sustainability* 14, 3274. doi: 10.3390/s140403274
- Mu, J., Elsamir, Y., Wang, J., Zhang, J., Li, W., and Zhang, X. (2023). A landscape-based ecological hazard evaluation and characterization of influencing factors in Lushui Forest Park. *Environ. Sci. Total Environ.* 2023, 175428. doi: 10.1007/s11368-023-02942-8
- Shi, L., Bai, L., Li, X., Yang, H., and Cheng, W. (2019). Identifying key landscape pattern indices influencing the ecological security of urban river basins: the middle and lower reaches of the Jin River basin as an example. *Environ. Sci. Total Environ.* 674, 429–439. doi: 10.1016/j.scitotenv.2019.04.237
- Nagendra, H., Wayne, D. K., and Forman, R. T. T. (2000). Patch patterns in forests: landscape fragmentation and the analysis of land use/cover change. *Agric. Ecosyst. Environ.* 102, 113–124. doi: 10.1016/S0167-6369(99)00080-0
- Nie, W., Yang, J., Xu, B., Bai, Z., Wu, Y., Liu, B., et al. (2022). Spatiotemporal evolution of landscape patterns and their driving forces under optimal granularity and the impact on the study and the environmental functional regionalization. *Front. Ecol. Evol.* 10, doi: 10.3389/fenv.2022.894252
- Pei, Y., Li, X., Yu, B., Huang, J., Sun, B., and Xu, Z. (2019). Quantitative relationships between wet landscape index and distribution pattern. *J. Soil Environ.* 20, 603–610. doi: 10.1007/s11368-019-0285-2
- Qian, X., Liu, L., Yang, Y., Gu, Y., and Zheng, T. (2022). Urban expansion assessment based on optimal granularity in the Hainan river basin of China. *Sustainability* 14, 13182. doi: 10.3390/s141013182
- Rao, M., Wang, Z., Wang, X., Yang, Y., and Hu, L. (2018). Green view effect of forest vegetation urban landscape pattern index in the central gullies: a case study of anshan city. *Chin. J. Ecol.* 27, 1117. doi: 10.13292/j.1000-4805.2018.03.08
- Su, C., and Fu, R. (2012). Discussion on links among landscape pattern, ecological process, and ecosystem services. *Chin. J. Nat.* 34, 227–237. doi: 10.3969/j.issn.1673-1309.2012.03.009
- Tong, M., Song, L., Zhou, Z., Wang, P., Xiao, W., and Duan, Y. (2016). Hierarchical landscape metrics to detect grain size in the three gorges reservoir landscape in China. *Environ. Monit. Assess.* 73, 1–13. doi: 10.1007/s12665-015-5605-4
- Tian, P., Cao, L., Li, L., Pu, H., Shi, K., Wang, L., et al. (2019). Landscape grain effect on restoring coastal wetland and its response to landscape changes. *Wetlands* 39, 2225. doi: 10.1007/s10675-019-0222-2
- Valentine, A. (2020). GIS-based methods for identifying river networks types and changing river basins. *Water Resour. Manage.* doi: 10.1007/s11269-024-03915-7
- Van der Haegh, T., Polch, R., Frankforter, F., Kienast, F. R., Bach, A. G., Padoa, V., et al. (2019). The impact of vegetation landscape patterns on the provision of landscape services: an explorative study using an index of land change. *Landscape Ecol.* 34, 367–371. doi: 10.1007/s10980-019-0765-2
- Wagner, H. H., and Forman, R. T. T. (2009). Spatial analysis of landscape concepts and metrics. *Ecology* 90, 1072–1087. doi: 10.1890/0891-6959(2009)090[1072]2.0.CO;2
- Wang, H., and Li, C. (2022). Analysis of scale effect and change characteristics of ecological landscape pattern in urban waters. *Environ. Sci. Total Environ.* 81, 10217–10227. doi: 10.1007/s11368-021-04008-0
- Wang, J., Li, L., Zhang, Y., Chen, L., Shen, W., Liu, W., et al. (2021). Optimal grain size based landscape pattern analysis for morphological landscape maps from 1986 to 2017. *PLoS One* 16, 2799–2812. doi: 10.1371/journal.pone.0257902
- Wang, S., Yang, Y., Yang, K., and Yang, X. (2020). Analysis of the spatiotemporal evolution and factors influencing ecological land in northwest yunnan from the perspective of land-use construction of a national ecological civilization. *Quaternary* 17, 1074. doi: 10.1002/qua.24074
- Wu, J., Ishikawa, D. K., Luck, M., and Tueller, P. T. (2000). Multiscale analysis of landscape heterogeneity: Scale, variance and pattern metrics. *Ann. GIS* 6, 41–56. doi: 10.1080/1362303001000090929
- Wu, W., Xu, J., Zhang, M., Ou, M., and Fu, H. (2019). Impact of landscape metrics on grain size effect in different types of patches: a case study of wetland. *Acta Ecol. Sin.* 39, 2740–2749. doi: 10.1360/acta.030119073013
- Xiao, D., and Li, X. (2010). Functions and future measures of landscape ecology. *Acta Ecologica Sin.* 30, 1613–1621. doi: 10.13215/j.cnki.1008-0353.2010.08.026
- Xiang, Y., Xu, S., You, H., Qiu, Z., Liu, Y., and Zhou, L. (2022). Influence of human activities and climate change on wetland landscape pattern—a review. *Sci. Total Environ.* 826, 153112. doi: 10.1016/j.scitotenv.2022.153112
- Yang, C., Deng, W., Tian, Q., and Zhang, S. (2022a). Changes in landscape pattern and an ecological risk assessment of the Changjiangjiang wetland nature reserve. *Front. Ecol. Evol.* 10, doi: 10.3389/fenv.2022.831774
- Yang, D., Liu, Y., Zhang, P., and Jiang, L. (2022b). Spillover effects of built-up land expansion on ecological security in urban area of multiple spatial scales. *Front. Ecol. Evol.* 10, doi: 10.3389/fenv.2022.867807
- Yang, X., Huang, X., Zeng, Y., Yang, L., Ye, Y., and Liu, Y. (2023). Reflection on the processes of agricultural wetland in hilly area under the background of rural revitalization. *Top. Appl. Geol. Technol.* 46, 74–78. doi: 10.1007/s11464-023-04104-4
- Zhai, J., Hou, P., Zhou, Z., Xiao, H., Tian, C., and Shi, X. (2019). An analysis of landscape pattern spatial grain size effects in gongli lake watershed. *Environ. Sci. Total Environ.* 70, 178–186. doi: 10.1007/s11368-019-0222-2
- Zhang, H., Liu, C., Yu, J., Guo, Q., Hu, C., and Huang, H. (2022). A novel forest landscape index for carbon storage using complex network theory in the yellow river basin. *Environ. Sci. Total Environ.* 81, 10217. doi: 10.1007/s11368-021-04008-0
- Zhang, S., Wu, Y., and Liu, Y. (2015). Effects of spatial grain change on the landscape pattern index in yunnan mountain area of shanghai province, east China. *Chin. J. Ecol.* 31, 439. doi: 10.13292/j.1000-4805.2015.03.032
- Zhang, Q., Chen, C., Wang, L., Yang, D., Zhang, T., Wang, X., et al. (2020). The spatial gradient effect, changing landscape patterns, and suitable landscape metrics in the three gorges reservoir area (1995–2015). *Environ. Sci. Total Environ.* 724, 106258. doi: 10.1016/j.scitotenv.2020.136259
- Zhang, S., Pu, W., Li, Y., and Yu, X. (2017). The influence of changes in land use and landscape patterns on soil erosion as a watershed. *Sci. Total Environ.* 574, 34–43. doi: 10.1016/j.scitotenv.2016.09.024
- Zhao, W., Fu, H., and Chao, L. (2010). The effects of grain change on landscape index. *Quaternary Sci.* 30, 228–235. doi: 10.3321/q.issn.1001-7319.2010.03.011

Appendix A

TABLE A.2: Evaluation of computer interpretation accuracy (1988).

1988 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	91.18	74.9
Forest	97.59	95.65
Grassland	96.49	96.22
Construction land	88.74	80.01
Waterbody	91.22	99.91
Total	91.09%	
Kappa	0.8836	

TABLE A.4: Evaluation of computer interpretation accuracy (2010).

2010 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	93.86	82.11
Forest	97.89	94.94
Grassland	82.24	97.34
Construction land	90.34	78.42
Waterbody	98.92	99.91
Total	90.98%	
Kappa	0.8266	

TABLE A.5: Evaluation of computer interpretation accuracy (1990).

1990 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	91.24	81.42
Forest	95.18	95.22
Grassland	91.12	92.11
Construction land	94.11	78.11
Waterbody	98.22	100.00
Total	92.40%	
Kappa	0.8407	

TABLE A.6: Evaluation of computer interpretation accuracy (2018).

2018 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	99.67	97.22
Forest	94.71	94.42
Grassland	72.82	97.39
Construction land	78.11	64.74
Waterbody	99.67	100.00
Total	90.18%	
Kappa	0.8051	

TABLE A.7: Evaluation of computer interpretation accuracy (2004).

2004 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	89.22	81.42
Forest	96.84	96.51
Grassland	71.40	91.10
Construction land	92.49	78.01
Waterbody	97.22	100.00
Total	89.80%	
Kappa	0.8427	

TABLE A.8: Evaluation of computer interpretation accuracy (2012).

2012 Confusion Matrix Accuracy Assessment		
	Prod. Acc. (Percent)	User Acc. (Percent)
Cultured land	91.51	75.11
Forest	97.85	93.99
Grassland	96.61	98.81
Construction land	70.73	95.42
Waterbody	99.42	99.91
Total	90.75%	
Kappa	0.8001	

Appendix B

TABLE A.7 | Landscape pattern indices (granularity) fitting function.

PO			EE		
Year	Function	R ²	Year	Function	R ²
1985	$y = 2119.2e^{-0.0001x}$	0.999	1985	$y = 219.85e^{-0.0001x}$	0.999
1995	$y = 2466.15e^{-0.0001x}$	0.999	1995	$y = 942.44e^{-0.0001x}$	0.999
2004	$y = 1428.85e^{-0.0001x}$	0.973	2004	$y = 489.26e^{-0.0001x}$	0.999
2010	$y = 245.66e^{-0.0001x}$	0.991	2010	$y = 649.22e^{-0.0001x}$	0.976
2016	$y = 2001.5e^{-0.0001x}$	0.995	2016	$y = 620.08e^{-0.0001x}$	0.977
2022	$y = 1042.5e^{-0.0001x}$	0.999	2022	$y = 482.23e^{-0.0001x}$	0.981



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Three waves of extended mind theories and urban planning: the city as a distributed socio-cognitive architecture

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This article explores the intersection between cognition theories and urban planning, conceptualizing the city as a distributed socio-cognitive architecture. It traces the evolution of these theories through three waves—functionalism, social externalism, and radical enactivism—Correspondingly, the article suggests implications for reorienting urban planning approaches, highlighting participatory design, collaborative placemaking, and the nurturing of place-based affordances. Drawing examples from existing planning literature, it demonstrates resonances with Extended Mind-informed orientations. The conclusion synthesizes these insights, proposing a potentially transformative framework by rethinking planning as more participatory, pluralistic, and cognitively integrative, challenging internalist and technocratic assumptions.

KEYWORDS

extended mind theories, urban planning, participatory design, sociocultural practices, place-based affordances, distributed cognition, enactivism, collective intelligence

1 Introduction

Urban planning is fundamentally concerned with shaping the built environment to improve human flourishing and wellbeing. However, throughout much of the 20th century, conventional planning approaches were critiqued as overly rationalistic, technocratic, and focused on physical interventions without adequately considering the social complexity and lived experiences of citizens (Friedman, 2000; Friedmann, 2011; Gehl, 2013; Healey, 1992).

In response, from the 1980s onwards new orientations emerged arguing that planners should move from paternalistically “designing for” people towards “designing with” people through more participatory, collaborative processes that engage local knowledge and leverage broader distributed expertise (Gendall, 1986; Forester, 1999; Innes and Booher, 2010; Samal, 2011). This aligned with wider critiques of scientific expertise as situated, plural, and historically contingent rather than universal and objective (Fischer, 2009; Jasanoff, 2004). In parallel, radical changes occurred in cognitive science and philosophy of mind starting in the late 20th century, challenging internalist conceptions that equate cognition solely with computation over a-modal symbols and representations within the brain (Varela et al., 1991). New perspectives treated cognition as embodied, embedded, extended, and enactive (4E cognition), arguing that the mind encompasses

brain, body, and the world, including sociocultural practices, artifacts, and interactions (Clark, 2008; Gallagher, 2013; Hutto and Myer, 2017; Theiner et al., 2019).

Could such externalist perspectives on distributed, culturally situated cognition provide foundational grounding for rethinking urban planning approaches in more participatory, pluralist, and socially embedded directions? This article explores potential intersections between extended mind theorizing and participatory planning practice (see Figure 1).

First, it delineates the conceptual progression through three waves of extended mind theories, from first wave functionalism that retains residual internalism, to second wave social externalism that thoroughly situates cognition within socio-material practices, to a third wave of radical constructivism that dissolves individuals into immanent relational effects (Gallagher, 2013; Gallagher and Mørch, 2012; Kirchhoff and Kiverstein, 2019).

Second, corresponding implications are suggested for the reorientation of urban planning approaches: participatory design methods leveraging distributed cognitive systems (first wave), collaborative placemaking engaging broader cultural meaning-making (second wave), and scaffolding place-based affordances and participatory pressures (third wave).

Third, examples from existing planning literature and practice are provided that resonate with these extended mind-informed orientations, including participatory budgeting (Sumner et al., 2011), river contracts (McCaffrey, J., C. 2007), cultural asset mapping (Sundercock, 2003), place making design (Thomas, 2016), tactical urbanism interventions (Lydon and Garcia, 2013), community-based urban regeneration (Duckin, 2009; McDonald et al., 2009) and augmented city theories (Calmi et al., 2018; Carr, 2021).

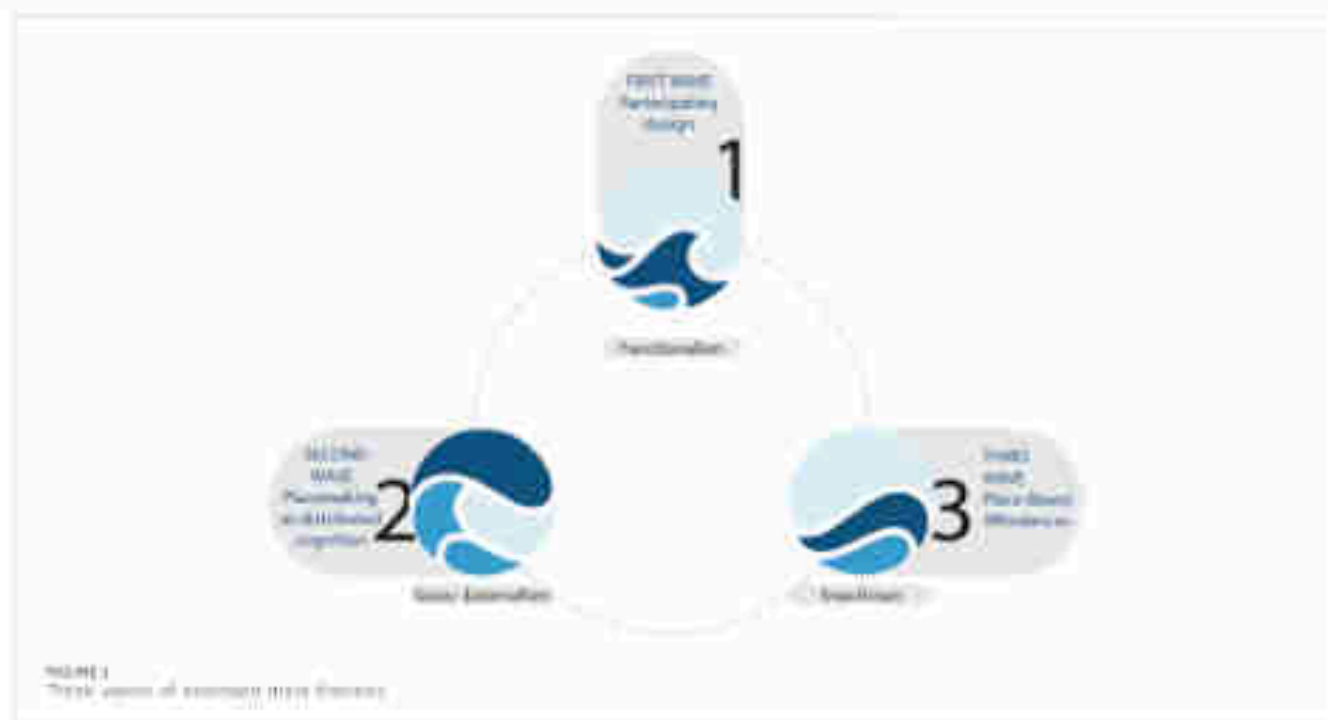
Finally, the conclusion reflects on integrating these complementary insights towards a transdisciplinary paradigm

reframing planning as more participatory, pluralistic, and cognitively integrative. While significant conceptual and practical challenges remain, extended mind perspectives provide promising esplanades for the elaboration of new planning approaches that better align with the distributed, cultural and complex essence of human cognition.

2 Three waves of extended mind theories

The notion of cognition extending beyond the skull originated in philosopher Andy Clark and artificial intelligence researcher David Chalmers' seminal 1998 paper, *The Extended Mind* (Clark and Chalmers, 1998). Critiquing internalism, they provocatively argued that external processes like Otto's notebook, i.e., a (paper) memory device used by Otto, a fictional character suffering from Alzheimer's disease, can be considered as genuine parts of cognitive systems, fairly analogous, in terms of information storage, to biological memory such as that of Inga, Otto's fellow who can directly access the same information as Otto from her own brain. This idea reconfigures alternative approaches to the tradition of thought that sees cognition as brain-bound computation over mental representations (Varma et al., 1991). While controversially claiming that cognition literally extends into the world, Clark and Chalmers retained an essentially functionalist, computational framing. The internal mind remains central, with external elements providing supplementary cognitive outsourcing if sufficiently trustworthy, reliable, and accessible (Clark and Chalmers, 1998). This theoretical position defined the first wave of extended functionalism.

However, critics highlighted that a genuine cognitive extension depends on socio-material practices, not just functional similarity



(Hutchins, 2014). This led to a second wave of socially distributed perspectives, arguing that cognition leaks across brain, body, and the world through webs of sociocultural scaffolding (Gallagher, 2013; Menary, 2013). Minds are intersubjectively constituted through participatory sense-making, not simply extended from individual brains.

Radicalizing further, a third enactive wave situates cognition within the larger organism-environment system (Kryhlhoff and Eversman, 2018; Thompson, 2007). Building upon an enactivist perspective (Varela et al., 1991), cognition is treated as the result of emergent relational effects, not mental representations. The mind thus becomes radically immanent in the world (Hutto and Myer, 2017).

The first wave of functionalist extension argues that cognition can spread into the world when external processes fulfill similar functions to inner neurocognitive mechanisms (Clark, 2008; Clark and Chalmer, 1988). For example, Otis's notebook playing the role of memory qualifies as part of an extended cognitive system if it is readily accessible and trustworthy. Critical criteria are reliability, accessibility, and past endorsement.

If external elements meet such demands, they count as genuine cognitive extensions irrespective of their material form. Cognition is thus "environmentally embedded" yet functionally similar to brain-based information processing (Clark, 2008, p. 114). The mind therefore remains grounded in the brain but becomes porously extended to reduce representational and computational loads.

This notion of cognitive outsourcing encountered criticisms of overextended cognition or "cognitive float," arguing for a clearer demarcation between the mind and the world (Aizawa and Arima, 2005; Rupert, 2004). The conceptual contours of this first wave remain debated (Clark, 2008; Menary, 2013) however, its birthing of externalist assumptions initiated a crucial rethinking of the mental as potentially extending beyond the skull.

Responding to such critiques, second wave perspectives based on distributed socio-externalism make a crucial step toward a more radical notion of externalization. For example, Hutchins' (1990) analysis of ship navigation demonstrates how cognition may be distributed across members, tools, and the environment through practices that transcend the cognitive activity of any single individual. Rather than discrete inner minds getting functionally supplemented, here cognition emerges through a sociocultural coalescence of minds (Gallagher, 2013; Gallagher and O'Keefe, 2009). Mental processes leak across the porous brain through webs of material-discursive-institutional cultural ecologies. The mind is thus constructed through participatory sense-making within shared scaffolds that shape possibilities for thinking and being (Ferryhough, 2016; Menary, 2013).

From this socioculturally distributed perspective, inner and outer cognition become inextricably entangled (Molubooti, 2013). Mental identities arise through situated embodied intersubjectivity, not as properties of isolated brains (Gallagher, 2008). The scope of the extended mind then shifts from a supplementation of individual cognition to the distributed propagation of minds across socio-material webs.

Radicalizing further into enactive relationalism, a third wave of relational perspectives dissolves individuals altogether (Gallagher, 2017; Gallagher and Minahara, 2012; Hutto and Myer, 2017; Thompson, 2007). Drawing stringently upon enactivism (Varela

et al., 1991), cognition is reconceived as an emergent world-making activity that is immanent in relational dynamics, rather than brains computing with mental representations. Situated action itself constitutes the mind, with cognition as an achievement of skilful participatory agent-environment entanglement (Hutto and Myer, 2017). Individuals then dissolve into the life-world, with systemic interrelation constituting cognition rather than minds being delineated across a subjective-objective divide (Thompson, 2007). There are no inner mental states underpinning cognition. From this non-representationalist framing, cognition is enacted through concrete socio-material practices (Molubooti, 2013). The mind becomes radically immanent under the form of enplaced relational effects, and is no longer conceptualized as extending across a cognizing subject-object divide. The very notion of extended mind then dissipates (Gallagher, 2017).

3 Urban planning implications

Each wave of extended theorizing opens possibilities for reimagining urban planning in more participatory, pluralistic, and place-focused directions aligned with distributed and culturally situated cognition. To sum up, the functionalist wave provides a conceptual case for participatory design, resonating with existing planning approaches. The social externalist wave positions planning as engaging distributed intelligence across socio-material practices. And the radical enactivist wave suggests that planning should nurture place-based participatory emergence through the scaffolding of local affordances. At this point, the next step is to develop these connections between extended mind perspectives and participatory planning. Examples are provided from parts of the urban planning literature and practice that already hint at such extended possibilities and reflect on productively synthesizing the complementary insights of the three waves. This will sketch the contours of a potentially transformative paradigm integrating diverse ways of knowing, participatory meaning-making, and complexity-focused design. While conceptual and practical challenges abound, by offering a fresh orientation to the nature of mind and expertise, extended theorizing provides promising new interdisciplinary foundations for a new wave of planning approaches aligned with the intricacies of socioculturally situated collective cognition woven through urban spaces.

3.1 First-wave functionalism - participatory design

By recognizing the porous cognitive boundaries of the skull, first wave perspectives imply that urban planning should look beyond individual minds to more distributed sociotechnical processes. If thinking encompasses external cultural resources, design should engage with broader collective cognition beyond isolated experts or users. This move from the brain to the ecosystem level aligns with existing participatory design approaches stemming from Scandinavian workplace democracy movements (Kha, 2009; Sandell, 2011). For example, the Utopia project in the 1970s enabled newspaper workers to co-design technological systems incorporating their tacit work knowledge, demonstrating how

cognition may be distributed across settings (Rocher, 1996; Lin, 1998). Another example relates to the experience of the river contract as a negotiated process acting for the common good of all. Over the years the participatory design turn has paved the way, individually and collectively, to the adoption of a transdisciplinary working method in which professional scientists and experts seamlessly collaborate with stakeholders and decision makers through a fluid, iterative and adaptive planning, design and implementation management process (McCarney, S. C. 2007). Viewing the mind as extended across physical devices with their related socio-material practices legitimizes such democratizing of design through the engagement of a constellation of distributed mental and material competence. Planning becomes a process of participatory cognition “in the wild,” not abstract detached reasoning (Huchard, 1993). The first wave thus provides grounding for collaborative design that discards the most narrow-minded forms of technocratic closure.

The notion of distributed cognition systems encompassing brain, body, artifacts, and the environment aligns with existing arguments for participatory design in planning (Fischer and Gottweis, 2013; Savoff, 2011), considering that thinking and expertise overflow beyond individual brains: design should engage broader tool-mediated collective cognition.

This democratic orientation is evident in participatory budgeting, where residents collectively deliberate on municipal spending priorities and projects facilitated by tangible cognitive artifacts like tables of proposals (Cunha et al., 2012). Such opening of expertise to wider distributed competence resonates with the first wave’s porously extended mind.

Participatory processes thus question paternalistic “designing for” people approaches by engaging with a broader distributed knowledge (Davidoff, 1965; Savoff, 2011). Treating cognition as spreading across socio-material situations beyond the head implies that planning should leverage such forms of distributed intelligence (in a comparatively weak form). The first wave thus provides some grounding for the democratization of design and for a significant reimagining of the nature and implications of expertise.

3.2 Second-wave socio-externalism—placemaking as distributed cognition

Further situating cognition within sociocultural ecosystems, second wave perspectives suggest that planning should tap collective intersubjective meaning-making that circulates through places, not just individual minds or extended functional systems. Conceptualizing thoughts as emerging through coordinated socio-material practices implies that design must resonate with, and reflect, local relationships, values, norms, identities, and ways of knowing (Fischer and Gottweis, 2013; Manzi, 2011). For example, asset-based community development engages residents in appreciatively mapping cultural resources such as skills, memories, institutions, and social networks as existing assets to democratically build upon (Sandbrook, 2005; Mathis and Cunningham, 2008). Such placemaking aligns with a treatment of cognition as participatory sense-making distributed across shared scaffolds that unlock new potentials for thinking and being. In this

regard, design practices may be reinterpreted as a calibration of existing cognitive-cultural resources woven through places. The second wave thus positions planning as engaging distributed intelligence as immanent in local situations, and not as an imposition of centralized top-down solutions (Bossett and Borens, 2011; Jones and Roehner, 2016). As expertise is scattered across socio-material practices (Whitmore, 2009), a radical escape from internalism is achieved in the second wave approach fully legitimizing placemaking as collaborative meaning-making and causes a deep rethinking of the distribution of power, authority and agency across the system.

Foregrounding that knowledge and meaning emerge through coordinated socio-material practices and relationships, the second wave suggests that planning approaches should be informed by broader ecosystems of place-based collective meaning-making as an expression of local distributed intelligence, not just individual minds (Manzi, 2011). This is evident in cultural asset mapping processes, which appreciatively put together inventories of existing local skills, associations, institutions, memories, gathering places and other cognitive-cultural resources as assets to democratically build upon in community development (Sandbrook, 2005; Watts and Kewitt, 1967). Such participatory mapping operationalizes the distributed and relational nature of place-based knowledge.

By treating cognition as propagated across shared scaffolds, the second wave positions planning in the skilled facilitation and navigation of distributed meaning-making practices woven through places, rather than the imposition of centralized objective solutions factually supplemented by plethora forms of participative consultation (Jones and Roehner, 2016). Expertise then becomes a commons, that is, a property of intrinsically participatory socio-material practices.

3.3 Third-wave enactivism - place-based affordances

Radically situating cognition within agent-environment dynamics, third wave perspectives imply that planning should nurture contextual affordances to catalyze a wholly place-based participatory emergence. Here, we define contextual affordances as the possibilities for action and meaning-making that emerge from the specific socio-material configurations of urban environments, shaped by both physical attributes and socio-cultural practices. This concept builds upon Gibson’s (1977) original notion of affordances as action possibilities provided by the environment, but extends it to encompass the rich, culturally mediated landscape of urban settings.

Getting to the details, this wave can be horizontally integrated through the 4A (agency, affect, affordance and autonomy) model (Climmers et al., 2016; Gallagher, 2021) by stating that environmental, social and cultural/normative factors are closely intertwined in social interaction and participate in the process of human cognition. Embracing this perspective requires acknowledging that agency can be influenced by affective shifts and available affordances (Gibson, 1977). Autonomy is linked to spheres of possibility defined by affordances that limit the power of agency. Hence, agency and affordances can co-evolve. This dynamic is based on a relational interplay that is shaped not only by relationships with other people, but also by relationships with the

environment. To integrate the Gibsonian concept of affordance into this model of cognition is to acknowledge that humans not only shape the environment through planned interventions but are in turn shaped by it. Affordance indeed refers to both the physical and psychological aspects of an object/device, combining its objective properties with how a subject perceives, and interacts with, it.

Contextual affordances in urban planning thus refer to the potential for interaction, engagement, and transformation that arises from the interplay between physical elements of the built environment (e.g., streets, buildings, public spaces), the social dynamics and cultural practices of local communities, the historical and cultural meanings associated with places, and technological infrastructures and digital layers of the city. Such affordances are not fixed properties of the environment, but rather relational and dynamic opportunities that emerge through the interaction between people and their surroundings (Barnold and Kervarion, 2014). They are context-dependent, and varying with individual and collective capacities, cultural backgrounds, and social norms.

As the mind is enacted through embodied socio-material practices, design should then foster the enabling of constraints that scaffold potentials for creative collective acting and meaning-making to unfold locally (Makino, 2012; Ruyveld and Kervarion, 2014). While significant conceptual and practical challenges remain, by offering fresh foundations for the reimagining of the mind, of expertise and collective knowledge, radically extended enactive perspectives provide promising resources for the development of constitutionally participatory planning paradigms attuned to the socio-cultural situatedness of cognition (Di Paolo and De Jaeger, 2021).

The radical enactive notion of cognition that emerges immanently through concrete embodied practices implies that planning should unlock contextual affordances and participatory processes in order to enable a true, creative emergence of place-based communal meaning-making as a form of intrinsically collective and de-individualized intelligence.

For example, tactical urbanism uses incremental low-cost changes to streets and public spaces to promote experimentation and grassroots placemaking tailored to the fine-grained local specificities of a neighborhood (Pitt, 2014; Lyden and Gascu, 2015). Community-based urban regeneration can be regarded as a proper correlative of this third wave. Co-design projects with local communities, where needs provide functions, are a clear example of structural coupling. In such projects, the needs are not only those of the people, but also those of other non-human city occupants, such as animals and plants (Huesel, 2019; Hernandez-Kentis et al., 2023). An early experiment of a needs-driven approach to community-based regeneration is that of Saint Michel in Montreal, where a deeply participatory planning process has led to the emergence of truly original and effective solutions, especially if assessed against similar processes in analogous settings (Pezdi et al., 2017); we will discuss this case study in more detail below. Moving forward, this third wave is also consistent with the ethos of the Augmented City theories (Larrock and Pivetti, 2012; Imortino and Kim, 2018; Montefrioni, 2022) where the urban environment becomes an expansive and dynamic cognitive ecosystem—responsive, participatory—and the city evolves into a sentient entity capable of processing information, responding to stimuli, and adapting in

real time. Indeed, if the environment, with all its human and non-human agents, is considered not merely as a physical space but as a distributed socio-cognitive architecture fully deploying collective intelligence and participatory meaning-making, additional possibilities for urban planning could be introduced (Morris et al., 2016). Digital platforms and virtual environments, for instance, facilitate participatory design, enabling citizens to contribute to public decision-making. In addition, the use of IoT and sensor technologies can collect real-time data on urban dynamics to gather information that can inform reactive placemaking initiatives (Galloni et al., 2021), adapting public spaces based on community needs and behaviors (Biber, 2018; Javed et al., 2022). Machine learning algorithms can then analyze complex models of human behavior, providing insights into cognitive affordances in specific locations (Guico, 2016; Burdibova, 2020). Such place-based co-creation resonates with cognition as relational effects achieved through embodied worldly practices, rather than designing abstract functions into space. This third wave incarnation embraces open-endedness and bottom-up complexity, against top-down planning tendencies, in its most uncompromising form (Dietz and Ruitter, 2015; Janderack, 2003). It grounds such emergence in the radical immanence of the mind in participatory placemaking, moving beyond the extension of cognition across Cartesian divides. Planning then fully becomes the scaffolding of socio-material practices that enable contextual affordances as the real drivers of community-driven urban change (Barnold et al., 2018). The third wave thus provides grounding for embracing open-endedness and bottom-up distributed agency as a form of collective computation geared toward social problem solving (Hennrich and Isenhardt, 2011).

4 Towards extended planning

Synthesizing these insights, extended perspectives offer resources for a paradigm that reframes planning as a more thoroughly participatory, pluralistic, and cognitively integrative than it is commonly found today in most planning practices. The successive waves provide complementary, layered orientations for the incorporation of diverse expertise at varying levels of design radicalism, leveraging participatory meaning-making, and nurturing place-based flourishing.

While each wave opens distinct possibilities, their synthesis is perhaps more significant (Clark, 2008; Gallagher, 2020). Together, they contest instrumentalism and technocracy by insisting on the sociality and richness of embodied cognition situated within cultural ecosystems and places. The mind is populated with diverse voices and perspectives that cannot be confined to individual brains. This reimagining of the nature of knowledge and selfhood has profound implications for democratizing and decolonizing planning (Janderack, 2004). The modernist figure of the professional expert gives way to participatory processes that recruit and engage multiple realities, perspectives, and ways of knowing, distributed across a vast range of socio-material practices (Awan et al., 2013; Fischer and Gottweis, 2013).

Rather than universal solutions, design becomes situated tinkering and place-based cultivation of collaborative potentials (Jönsson et al., 2014), already propagating through locales via everyday sense-making

in all its rich diversity (de Cusum, 1944; Inghil, 2011). Through small iterative efforts, 'interglocal resonances' can be created between top-down structures, grassroots creativity, and the socio-cognitive life of neighborhoods to enable contextual flourishing (Anderson and Baldwin, 2016).

This sketch of extended planning inevitably remains partial and provisional. Significant conceptual and practical tensions persist regarding coherence, power, values, and methods which require contextual navigation (Munizuma, 2011) and major experimentation and innovation in future planning practices. However, by offering fresh interdisciplinary orientation to collective urban meaning-making as irreducibly distributed across sociocultural ecosystems, the three waves provide vital conceptual resources to spark some much-needed evolution in planning approaches that allows better alignment with the social depth and richness of human collective cognition as situated in place.

5 Montreal Saint Michel: a *de facto* enactivist-informed approach to urban regeneration

The Saint Michel district regeneration project in Montreal as discussed in Ferilli et al. (2017) provides a compelling example of how third-wave enactivist principles can be applied to urban planning, resulting in a more inclusive, participatory, and socially sustainable transformation process. This case study illustrates how urban environments can be conceived of as distributed socio-cognitive architectures, where cognition emerges through the dynamic interaction between residents, cultural institutions, and the built environment.

First of all, the Saint Michel project exemplifies the enactivist principle of participatory sense-making. Instead of imposing a pre-determined vision, the regeneration process actively involved local stakeholders from the early stages. This approach aligns with the enactivist view that cognition is not confined to individual minds but emerges through collective interaction with the environment. The creation of TOHU, a multifunctional cultural space, served as a platform for this participatory process, enabling residents to co-create the meaning and identity of their neighborhood.

In addition, the project's focus on circus arts and performing arts created a rich landscape of affordances for local residents. In the enactive framework, affordances are not just physical properties but opportunities for action that emerge in the relationship between the agent and the environment. By offering training and employment opportunities in the circus arts, the project expanded the 'field of relevant affordances' (Rustad and Riverstein, 2014) for residents, particularly those from marginalized groups. This approach fostered the development of new skills and capabilities, enhancing the human capital of the community in an organic, context-sensitive manner.

Moreover, the Saint Michel project can be viewed as the cultivation of a cultural ecosystem where cognition is distributed across various actors and institutions. The presence of Cirque du Soleil, TOHU, and other related organizations created a network of interconnected cultural entities that collectively shaped the cognitive landscape of the area. This aligns with the enactivist view of

cognition as extended beyond individual minds and into the socio-material environment.

Furthermore, the emphasis on circus and performing arts in Saint Michel exemplifies the enactivist principle of embodied and situated cognition. These art forms inherently involve bodily engagement and are deeply contextualized in the local environment. By promoting these activities, the project facilitated forms of learning and skill development that are intrinsically tied to physical and social contexts, rather than abstract or decontextualized knowledge.

What is more, the Saint Michel project demonstrates a move away from rigid, top-down planning towards a substantially more adaptive and dynamic approach. This aligns with the enactivist view of cognition as an emergent process that unfolds through ongoing interaction with the environment. The project's ability to evolve and respond to community needs over time, rather than adhering to a fixed master plan, reflects this principle.

Also, the high levels of participation in cultural and social activities reported in the Saint Michel case study indicate the success of the project in fostering social cohesion. From an enactivist perspective, this can be understood as the emergence of collective cognitive patterns through shared cultural experiences. The cultural activities served not just as entertainment, but as cognitive tools for community building and identity formation.

And finally, the project's success in promoting intercultural dialogue among diverse immigrant communities in Saint Michel aligns with the enactivist emphasis on the sociocultural situatedness of cognition. By creating spaces and opportunities for different cultural groups to interact, the project facilitated the emergence of new, shared cognitive frameworks that transcended individual cultural boundaries.

The Saint Michel case therefore demonstrates how a *de facto* enactivist-informed approach to urban planning can lead to more inclusive, adaptive, and socially sustainable regeneration processes. By conceiving the urban environment as a distributed socio-cognitive architecture, the project was able to harness the collective intelligence of the community, create meaningful affordances for skill development, and foster a sense of shared identity and purpose. This approach stands in stark contrast to more traditional, top-down planning methods that often fail to engage with the complex, emergent nature of urban social systems.

The success of Saint Michel in terms of community participation, social cohesion, and cultural vibrancy suggests that enactivist principles could provide a valuable framework for future urban regeneration projects. By focusing on the dynamic interplay between people, culture, and the built environment, planners can create urban spaces that are not just physically renewed, but cognitively and socially enriched.

6 Substantial conceptual and practical challenges ahead

While the extended mind approach to urban planning offers promising avenues for more participatory and context-sensitive urban development, it also presents significant conceptual and practical challenges that need to be addressed. This section

outlines some of these key challenges and their implications for the future of urban planning.

6.1 Systemic deliberation and democratic choice-making

The role of planners in ensuring democratic choice-making within a systemic deliberation framework remains a critical challenge. As [Fainstein \(2010\)](#) argues, the pursuit of the “just city” requires not just participation, but also equity and diversity in decision-making processes. In the context of extended cognition, how can planners facilitate genuine democratic deliberation that accounts for the distributed nature of urban intelligence?

[Haley's \(2003\)](#) collaborative planning theory offers some insights, emphasizing the importance of inclusive stakeholder dialogues. However, translating this into practice within an extended mind framework requires new methodologies. Planners may need to evolve into facilitators of collective intelligence, designing processes that can capture and synthesize the cognitive contributions embedded in diverse socio-material practices across the urban landscape.

6.2 Representational frameworks and planning legitimacy

Traditional planning is deeply enmeshed in representational frameworks, from zoning maps to policy documents. The shift towards second and third wave approaches to urbanism, which emphasize emergent, enactive processes, poses a significant challenge to these established practices. As [Holler \(2011\)](#) notes, planning needs to move beyond representation to performance and affect.

In this new context, the role of planning might evolve towards what [Arnst and Theib \(2003\)](#) call “urban curatorship” – facilitating the conditions for urban creativity and adaptation rather than prescribing fixed outcomes. This raises questions about how to maintain legitimacy and accountability in planning processes that are more fluid and distributed. New forms of dynamic, real-time cognitive and decision-making tools may be needed to bridge the gap between traditional planning frameworks and extended mind approaches.

6.3 Lived experience and social justice

The privileging of lived experience in participatory planning approaches raises important questions about social justice and the potential perpetuation of existing inequalities. As [Young \(1990\)](#) argues, the mere aggregation of individual preferences does not necessarily lead to just outcomes. How can an extended mind approach to planning address systemic injustices and power imbalances?

[Smallerock's \(2023\)](#) concept of “therapeutic planning” offers one potential avenue, emphasizing the need to address historical traumas and exclusions in urban development. Within an extended mind framework, this might involve the development of new

methods for surfacing and addressing collective urban traumas embedded in the socio-material fabric of cities.

Moreover, the question of who decides when injustice is occurring becomes more complex in a distributed cognitive system. [Fainstein's \(2010\)](#) criteria for the just city—equity, diversity, and democracy—might need to be interpreted and operationalized within an extended mind or enactivist framework. This could call for developing new indicators and feedback mechanisms that can capture injustice as it emerges from complex urban interactions.

More broadly, our approach makes a clear call for an idea of urbanism that sees the agency and legitimization of minorities as a primary goal, and that refuses to accept top-down, hierarchical planning as a convenient technocratic pretext to limit them in the name of superior collective interests. The intrinsically emergent nature of an enactivist approach to planning implies that only a fair and equitable representation of all the voices involved in the process ensures minimal conditions for the social sustainability and democratic character of the planning process. This certainly implies more potential conflict and more need for negotiation at early stages, but on the other hand it also means that the conflicts that are likely to emerge at later stages in a critical situation of strong imbalance of power and political representation due to the marginalization and delegitimation of minority voices may in this way be anticipated and, if successfully and effectively dealt with, preempted to a large extent.

6.4 Practical implementation and institutional change

Implementing these new approaches will require significant institutional changes in planning practice and education. As [Harris and Roubet \(2010\)](#) argue, planning institutions are often resistant to change and wedded to traditional technocratic approaches. How can planning education and professional development evolve to incorporate extended mind or enactivist perspectives?

Moreover, the practical tools and methodologies for extended urban planning are still in their infancy. Apart from promising early examples, there is a need for more comprehensive frameworks that can operate at multiple scales and timeframes.

Addressing these challenges will require interdisciplinary collaboration between urban planners, cognitive scientists, philosophers, and community stakeholders. It will also necessitate a willingness to experiment with new forms of urban governance and decision-making. As we move forward, careful empirical research and ethical reflection will be crucial to ensure that extended mind or enactivist approaches to urban planning genuinely contribute to more just, sustainable, and vibrant cities.

7 Conclusion

This article has explored potential intersections between extended mind cognition perspectives and participatory urban planning approaches. The subsequent waves of functionalist

extension, social externalism, and radical enactment outlined each provide distinct yet complementary resources for reimagining planning in more participatory, pluralistic, and place-focused directions that align with the distributed, cultural, and complex essence of human cognition.

The first wave of functional externalism suggests participatory design approaches that question narrow technical expertise by engaging broader distributed sociotechnical knowledge. The second wave of social externalism implies that planning should catalyze collaborative placemaking processes that tap existing ecosystems of emergent, collective meaning-making. And the third enactive wave stresses how the unfolding of contextual affordances and participatory processes may enable radically new forms of place-based communal meaning-making and grassroots creativity.

Synthesizing these complementary insights, in this article we sketched the contours of a potentially transformative paradigm that reframes planning as more thoroughly participatory, cognitively integrative, and socially attuned. This proposed orientation draws on extended perspectives to challenge internalist and technocratic assumptions, opening possibilities for planning that fully leverage upon embodied situated cognition to enact collective meaning and identity within the relational flows of lived space.

While substantial conceptual and practical challenges remain, the article hopefully offered some fresh interdisciplinary perspectives for the upgrading of current planning approaches to make them more aligned with the distributed, cultural and complex essence of human collective sense-making woven through urban environments. By providing novel conceptual links between extended mind theories and participatory planning orientations, we aim at opening possibilities for further transdisciplinary work, creatively building on these connections to encourage more socially embedded, empowering and cognitively integrative planning processes co-evolving with the socio-cultural richness of local contexts.

References

- Ajzen, I., and Fishbein, M. (1975). The theory of reasoned action. *Psychol. Bull.* 82, 179–211. doi:10.1037/0033-2909.82.2.179.
- Allen, S., and Smith, M. (2001). *Once integrating the urban*. Cambridge, Mass: MIT Press.
- Anderson, J., and Bullman, C. (2010). "Building well-being: neighborhood flourishing and approaches for participatory urban design intervention," in *Handbook of community well-being research* (Dordrecht, Netherlands: Springer), 315–331.
- Aron, N., Schmeidler, T., and Eyal, T. (2017). *Spatial agency: other ways of doing cognition*. United Kingdom: Routledge.
- Bain, L. E. (2018). The IoT for smart sustainable cities of the future: an analytical framework for smart-based big data applications for environmental sustainability. *Sustain. Cities Soc.* 38, 236–253. doi:10.1016/j.scs.2017.11.014.
- Baltes, S. (1996). Creating conditions for participation: conflicts and resources in system development. *Human-Computer Interact.* 11, 205–236. doi:10.1016/1032-2565(96)00012-2.
- Bourman, E., and Boudier, J. (2021). Self-organization in urban development: towards a new perspective on spatial planning. *Urban Res. and Pract.* 12, 96–122. doi:10.1080/17535044.2021.2006672.
- Boudier, J. (2020). Machine learning for exploring spatial affordance patterns. *Urban Paper* 2019/2020/2021. doi:10.2478/9783708920019_0019.
- Carratton, M. (2021). "Augmented cities in the near-future," in *Current challenges in architecture and urbanism in Africa: The urban book series*. Editors A. Yankson, A. Hysa E. Mawhood, P. Nwadi, O. D. Mawhood, and S. Derrin (Cham: Springer).
- Colau, P., Folmer, E., and D'Alessandro, E. (2018). The challenge of segmented cities: more opportunities of common spaces. *New Metropolitan Perspectives: Local Reversal, Innovative Dist. Research, Terroir, Attractiveness Through Expansion, Between Urban Agglomeration, Volume 1*, 134–156. doi:10.1007/978-3-319-93499-5_14.
- Christensen, W., Sutton, J., and Mullen, D. J. (2016). Cognition is skilled when mediated (owned) and the varieties of skill experience. *Mind and Lang.* 31, 37–69. doi:10.1017/S0264375816000048.
- Clark, A. (2008). *Increasing the mind: embodiment, action, and cognitive science*. Oxford, United States: Oxford University Press.
- Clark, A., and Chalmers, D. (1998). The extended mind. *American Philosopher* 54, 10–19. doi:10.1093/acph/54.1.10.
- Darstoff, F. (1983). Activities and processes in planning. I. *Am. Soc. Planners* 19, 141–151. doi:10.1080/01449138308937517.
- Dubois, H. (2009). A community-based approach to sustainable urban regeneration. *J. Urban Comput. 10* (5), 80–122. doi:10.1007/s10901-009-9104-4.
- De Certeau, M. (1984). *The practice of everyday life*. Oakland, United States: University of California Press.
- De Paolo, S. A., and De Jaegher, H. (2022). Enactive social difference: becoming participatory. *Topoi* 41, 241–256. doi:10.1007/s11245-022-09756-z.
- Ellis, P. (1988). *Work-oriented design of computer artifacts*. London: Academic Press.

Data availability statement

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- Ellis, P. (2008). "Participation in design: Hopes," in *Proceedings of the tenth university conference on participatory design* (Bloomington, United States: Indiana University), 92–100.
- Fanning, J. L. (2000). New directions in planning theory. *Urban Aff. Rev.* 35 (4), 455–476. doi:10.1177/0038012200035004
- Fennell, L. V. (2000). *The 1st city*. Ithaca, New York: Cornell University Press.
- Ford, G., Lewis, P. J., Taran, M., G., and Forster, S. (2017). Power to the people when culture works as a social catalyst in urban regeneration processes (and when it does not). *Eur. Plan. Stud.* 25 (2), 245–259. doi:10.1080/09654316.2016.1259997
- Forsyth, C. (2000). Yogyakarta: Java and the social brain. *Cont. South. Cult. Stud. J. Austral. Stud.*, 36–75. doi:10.1017/S0022278X00005003
- Fors, D. (2014). DIY urbanism: implications for cities. *Journal of Urbanism: International Research on Planning and Urban Sustainability* 7 (3), 361–386.
- Fraser, J. (2009). *Democracy and expertise: increasing policy rigidity*. Chelms: United State: Oxford University Press.
- Fraser, J., and Giddens, R. (2013). *The argumentative turn: toward public policy as conversational process* (Chelms: United States: Duke University Press).
- Friedman, J. (1999). *Planning in the face of power*. Oxford, United States: University of California Press.
- Friedman, J. (2011). *Integrative vision in planning theory*. United Kingdom: Routledge.
- Furus, G. (2016). Beyond the built-up: heterotopia, alienation, spatial affordance and William S. Burges. *Environ. Urban Des.* 49, 59–66. doi:10.1080/09597279.2016.1171011
- Gallagher, S. (2000). *How do built shapes the mind*. Chelms: United State: Oxford University Press.
- Gallagher, S. (2011). The socially extended mind. *Cognitive Sci.* 35, 4–22. doi:10.1016/j.cogsci.2010.08.006
- Gallagher, S. (2012). *Immersion, interaction: rethinking the mind*. Chelms: United State: Oxford University Press.
- Gallagher, S. (2020). *Action and interaction*. Chelms: United State: Oxford University Press.
- Gallagher, S. (2022). The fit and the fat: culture, agency, affordance, autonomy in the mediated dynamics of social cognition. *Front. Psychology* 13, 883–899. doi:10.3389/fpsyg.2022.883473
- Gallagher, S., and Cribari, A. (2009). Mental immersion. *Topoi* 28 (1), 45–51. doi:10.1007/s11243-008-9041-0
- Gallagher, S., and Ouyang, H. (2012). "Non-propositional and context-intentionality," in *Action, perception and the brain: adaptive and cognitive responses*. Editor J. Schuster (Palgrave Macmillan), 117–146.
- Gallagher, R., Sacco, P. L., and the European, M. (2021). Complex urban systems: challenges and integrated solutions for the sustainability and resilience of cities. *Complexity* 2021 (2), 1762154. doi:10.1155/2021/1762154
- Gill, J. (2013). *Time for people*. Wellington: Mind Press.
- Gilman, I. (1979). *The ecological approach to rural planning*. Boston: Lexington Books.
- Haider, F. (1992). Planning through debate: the communication turn in planning theory. *Trans. Plan. Rev.* 44 (2), 141–162. doi:10.1023/A:102380789914873
- Haider, F. (2000). Collaborative planning in perspective. *Plan. Theory* 2 (2), 101–121. doi:10.1177/1473147000022002
- Hall, M. O. (2019). The right to ground: integrating human and non-human perspectives in an inclusive approach to sustainability. *Sustain. Des.* 27 (2), 245–254. doi:10.1016/j.sds.2019.100000
- Hernandez-Santos, C., Amis, M., Roberts, S., and Dicks, C. (2025). Integrating biodiversity in a non-human stakeholder within urban development. *Landscape Urban Plan.* 332, 105074. doi:10.1016/j.landurbplan.2023.105074
- Hillier, J. (2011). Strategic navigation across multiple planes: towards a Delmonian inspired methodology for strategic spatial planning. *Urban Plan. Rev.* 41 (3), 309–327. doi:10.1080/02697429.2011.591300
- Hutchins, E. (1995). *Cognition in the wild*. Cambridge MA: MIT press.
- Hutchins, E. (2010). The cultural evolution of human cognition. *Philos. Theoret.* 27 (1), 14–39. doi:10.1080/09571809.2011.594548
- Hutto, D. D., and Mott, E. (2017). *Enriching practice: how social and context*. Cambridge MA: MIT Press.
- Isenhardt, S., and Fennell, C. (2021). *Cityscapes: a cognitive perspective of the city*. Cambridge and Society. doi:10.1017/9781017012207
- Isenhardt, H., and Kain, J. W. (2016). The Urban Cityscape: a mobile augmented reality tool for crowd-sourced simulation of emergent urban development patterns, requirements, prioritizing and assessment. *European Journal of Urban and Reg. Stud.* 21, 126–139. doi:10.1019/ejurs.2016.00000
- Jagodz, T. (2011). *Making anthropology, archaeology, art and architecture*. United Kingdom: Routledge.
- Jones, J. E., and Baskin, D. E. (2014). *Planning with complexity: an introduction to collaborative activities for public policy*. United Kingdom: Routledge.
- Jones, J. E., and Baskin, D. E. (2015). A turning point for planning theory? Overcoming disabling structures. *Plan. Theory* 14 (2), 145–151. doi:10.1177/1473147014711110
- Kearney, A. (2000). *Stories of knowledge: the articulation of stories and the social order*. United Kingdom: Routledge.
- Kirk, A. R., Shafar, F., de Salazar, L., Zlatos, Y. R., Rasmussen, T. (2022). Future urban cities: systematically comparing technologies, applications, challenges, and future aspects. *Cities* 129, 105794. doi:10.1016/j.cities.2022.105794
- Kirchhoff, M., and Kretzschmar, J. (2019). *Extended consciousness and predictive processing: a third way view*. United Kingdom: Routledge.
- Kirby, W., and Genda, A. (2015). *Tactical urbanism: short-term action for long-term change*. Washington: Island Press.
- Malabar, L. (2011). *How things shape the mind*. Cambridge MA: MIT Press.
- Marshall, M. (2022). "Embracing urban cognition in civic landscapes in the digital augmented city: a critical informed exploration of counterhegemonic individualism in the age of networked landscapes, multi-sensory mediation and nonhuman transhumanism," in *The multiple landscapes of nonhuman cities and landscapes in the digital era*. United Kingdom: Routledge), 497–503.
- Mattern, E. (2013). *Design, where everybody shapes: an introduction to design for social innovation*. Cambridge MA: MIT Press.
- Mattern, E., Galloway, W., and Rieffel, S. (2011). Cognitive affordance in sustainable urbanism: contributions of space syntax and spatial cognition. *J. Urban Des.* 21 (4), 439–452. doi:10.1080/15587049.2011.614400
- Mattis, A., and Cunningham, G. (2010). From chance to culture: asset-based community development as a strategy for community-driven development. *Dev. Pract.* 20 (3), 474–486. doi:10.1080/09694420903200020
- McCarthy, J. C. (2007). *The law of nonstatistical sampling*. 3rd edn. Oxford, New York: Oxford University Press.
- McDonald, S., Malya, R., and Malone, V. (2009). Urban regeneration for sustainable communities: a case study. *Urban Des. Rev.* 43 (1), 46–59. doi:10.1080/13601670802691288
- Minsky, R. (2010). *The extended mind*. Cambridge MA: MIT press.
- Moreau, E., Deryn, D., and Van Kesteren, M. (2010). "Technological creativity: cooperation in engaging with a field of ideation affordances: the skilled ideation/creativity framework (SIC)" in *The Oxford handbook of cognitive, embodied, embedded, creative and extended*. Editors A. Norman, L. de Bruin, and J. Gallagher (Oxford, New York: Oxford University Press), 344–360.
- Moreau, E., and Kretzschmar, J. (2016). A rich landscape of affordances. *Front. Psychol.* 7, 147–152. doi:10.3389/fpsyg.2016.00147
- Reaper, R. D. (2004). Challenges to the hypothesis of extended cognition. *J. Philosophy* 101 (6), 384–426. doi:10.1046/j.1099-1324.2004.00147x
- Sandercock, L. (2005). Cosmopolis II: integral cities of the 21st century. *Geopolitics* 11 (2004), 1–20. doi:10.1016/j.geopol.2004.0000000000
- Sandercock, L. (2004). Towards a planning imagination for the 21st century. *J. Am. Plan. Assoc.* 70 (2), 123–141. doi:10.1080/03655680420000000000
- Sandercock, L. (2020). *Mapping possibilities: finding purpose and hope in community planning*. United Kingdom: Routledge.
- Saunders, H. (2011). Multiple cases of participatory design. *Front. Psychol.* 2, 1–10. doi:10.3389/fpsyg.2011.00000
- Schneider, J., Sachs, C., Riedel, J. M., Sauer, K., Hartmann, M., and Hirsch, O. J. (2014). *Shared design methods*. Cambridge MA: MIT Press.
- Schneider, J., Hartberg, C., Riecke, K., and Alagiri, G. (2012). Transnational models of urban participation: the case of participatory budgeting. *J. Public Deliberation* 8 (2), doi:10.1684/jpd.141
- Thomas, C., Allen, C., and Goldstone, R. L. (2010). Reconnecting green cognitive systems. *Hum. Dev.* 11 (1), 228–239. doi:10.1016/j.hdev.2010.07.002
- Thomas, D. (2010). *Reconnecting: an urban things methodology*. doi:10.1326/9781136481125
- Thompson, E. (2007). *Mind in life: biology, phenomenology, and the search for mind*. Harvard: Harvard Press.
- Yardi, E. J., Houghton, K., and Bosch, E. (2011). *The embodied social: cognitive, culture and human experience*. Cambridge MA: MIT press.
- Waller, W., and Kierulff, C. (1995). *Community architecture: how people are creating their own environment*. Pergamon.
- Whitmore, E. J. (2009). Mapping knowledge: cognitive science, formality and the rationalization of cognition. *Prog. Hum. Geogr.* 34 (7), 947–966. doi:10.1177/0308518209350641
- Yong, J. M. (1998). *Justice and the politics of difference*. Princeton: University Press.

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Perceptions of improvements and mental health outcomes of micro-renewal in old Danwei community: a survey of residents in Hengyang, China

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Introduction: Danwei communities are a testament to China's socialist urban development, characterized by the self-sufficiency, strong social networks, and institutional management. In the historical context of urban development in China, many old communities have evolved from former housing areas of Danwei. After more than 40 years of use, the buildings, and environments in the old Danwei communities remain in disrepair, dirty, disorderly and poor condition. Many functions have failed that negatively affect the quality of life and health of residents. After Covid-19, improving the mental health of residents has become a major goal of public policies in various countries.

Methods: To explore the residents' mental health in the micro-renewal, this study carried out a survey regarding residents' evaluation on the micro-renewal and their mental health in two renewed Danwei communities in Hengyang, China. More than 800 respondents joined the interview, among them, 634 samples are effective for analysis. Entropy-TOPSIS is applied to analyze the weights of various indicators of micro-renewal. And multinomial logit model is used to examine the relationship between the personal factors, satisfaction on various items of micro-renewal and mental health.

Results and Discussion: The findings indicates that the mental health level of residents living in Danwei community is affected by micro-renewal. The socio-demographic characteristics and behavior factors can influence on the possibility of being in different levels of mental health. The satisfaction on the components of micro-renewal and improvements after micro-renewal is also determiner of residents' mental health level. In addition, the heterogeneity is address in mental health.

KEYWORDS

mental health, perception of environmental improvements, micro-renewal, entropy-TOPSIS, multinomial logit

1 Introduction

The rapid and unplanned urbanization is one of the main ecological and human challenges in the 21st century (1). The instability of the urban system has been intensified along with climate change and environmental deteriorating through the increasing anthropological activities. The World Health Organization (WHO) put forward the initiative aiming at

improving the health and well-being of urban population through participatory and multi-sectoral urban governance by 2028, and proposed that health does not start from hospitals or clinics, but from our families and communities (2). To support the sustainability in economic and social development and improve the environmental quality and population's health in urban areas, urban renewal has been carried out in various ways all over the world (3–4).

The urbanization process in China has been significantly accelerated in the last decades. The population living in cities was about 68.29 million in 1978, which accounted for 17.3% of the total population in China at that time. By the end of 2022, this proportion increased to 65.22%, in other words, more than 920 million population in China is living in cities now. However, in the wake of urban development and population growth, the shortcomings are becoming apparent in the existing large number of old communities (5,6). These old communities were typically built by state-owned enterprises, government departments, and public institutions to house their employees and their families. The term "Danwei" refers to all these organizations that provided employment, housing and various social services to its members. Danwei has been the principal social organizational form in Chinese socio-economic contexts until the beginning of 21st century (10–11).

The old Danwei communities in China, once the cornerstones of socialist urban development, are now facing significant challenges as they age. There is a serious quality conflict between old Danwei communities and new communities, which exacerbates social inequality in housing and hinders sustainable urban development (10). Compared with newly built communities, there are limitations such as incomplete supporting facilities, serious illegal constructions, and insufficient parking spaces. Moreover, after more than 40 years of use, the buildings in the old communities remain in disrepair, dirty, disorderly and poor condition. Many functions have faded that negatively affect the quality of life of residents and impact on their health. Such physical conditions of old Danwei communities can significantly affect residents' mental well-being (11). Living in poorly maintained environments can lead to feelings of helplessness and despair, exacerbating stress and anxiety (12). The lack of investment in these communities also means that essential services, such as sanitation and waste management, are often absent, further degrading the living conditions and contributing to the residents' mental strain. The residents, especially the older adults and children, find themselves confined to environments that do not support their developmental and social needs, leading to increased incidences of depression (13). Perhaps one of the most insidious issues facing residents of old Danwei communities is social isolation. As these communities were originally built for the employees of specific factories or institutions, the social fabric was once tightly knit. However, with the closure of many of these workplaces and the outmigration of younger populations, the remaining residents often find themselves isolated. The breakdown of these social networks means that many residents, particularly the older adults, experience loneliness, which has been strongly linked to poor mental health outcomes (14–16).

In recent years, to achieve fair health and social outcomes, the renewal of old residential community has become the key part of urban renewal where the obvious population aggregation, regionality and symbiosis exist (10, 17, 18). Improving the mental health of residents has become a major goal of public policies in various countries, especially in urban and rural development policies. The

local government, scholars and urban planning and public health experts have been exploring ways to improve residents' mental health through the intervention of old residential community renewal (8, 19–21). Based on literature regarding the research on urban renewal, the large-scale demolition and innovation are not suitable model for resilience of old Danwei communities.

An innovative renovation measure was firstly proposed as "micro-renewal" by urban renewal bureau of Guangzhou in 2018. Compared with the large-scale and government-led renovation model, it is a people-oriented urban renewal model with minor rebuild (22). Compared to reconstruction, micro renovation is less likely to disrupt residents' neighborhood attachment (24). At the same time, micro renovations contribute to the sustainable protection of living heritage, helping old Danwei communities retain their historical and collective memory related features and values while seeking development and adaptation (23). The micro-renewal, as an innovative approach, has been implemented in urban redevelopment (24, 25). It is the adjustment and functional replacement of the environment and suitable for places with inconsistent usage and poor environmental conditions (26).

The participation in planning and design of community renewal can affect residents' sense of empowerment, thereby achieving higher health benefits (Baba, Kearns, McIntosh, Tannahill and Lewsey) (28). The focus of public participation is to safeguard the interests and demands of the public as well as the public interests of the community. Therefore, the impacts of public participation in micro-renewal of old Danwei communities on the mental health of residents are reflected in two aspects. On the one hand, micro-renewal can change the quality and appearance of houses and community, potentially affecting the emotions of residents; on the other hand, residents can promote the goal of amending the environment of community closer to their needs through public participation, while also improving their sense of belonging and cohesion toward the community, thereby enhancing their mental health and sense of happiness in life.

To explore the residents' mental health in the renovation of old residential areas, self-assessment of their expected mental health is necessary (29). However, current research on urban renovation and resilience mainly focuses on quantifying the improvement of the physical environment and the psychological satisfaction of residents after renovation. Limited empirical evidence on the improvement of residents' psychological health through urban renewal, especially microscale renovation, was presented (8, 28). It is necessary to extend the residents' assessments on the improvements in micro-renewal with a reasonable self-assessment of the mental health for fully understanding the effects of micro-renewal of neighborhood. To achieve this goal, this study, therefore, takes two old Danwei community micro-renewal projects as cases to investigate the potential impacts of neighborhood renovation on the mental health of residents. The key variables in that affect the mental health of residents was identified to construct a comprehensive framework for post occupancy evaluation in neighborhood micro-renewal. The findings are expected to guide the sustainable development of old Danwei community in contexts of Chinese cities.

This study is aiming to examine the nature and strength of the relationships between residents' satisfaction on neighborhood scale renewal and their mental health. The conceptual framework of post occupancy evaluation advocates that the transformation of the architectural environment will have an impact on the actual living

experience of residents in various aspects in terms of environment, architecture, and resources, as well as personal psychology. Accordingly, the implementations of old Danwei community micro-renewal may affect the psychological health of residents through changes in different dimensions such as residential conditions, community environment, community safety, aesthetics, and quality of activity spaces, etc. The satisfaction evaluation which measures the benefits generated by micro-renewal can be obtained from the field surveys on residents. Therefore, this study proposes an innovative framework of “public participation-micro-renewal of old community-residents’ mental health.” The analysis framework links objective living conditions with mental health through micro-renewal of old Danwei communities and makes public participation an important prerequisite for the implementation of micro renovation projects.

2 Literature review

Urban renewal has been a significant focus of urban planning and public health research for decades, driven by the need to address the challenges posed by aging urban infrastructure, particularly in rapidly urbanizing countries like China. The old Danwei communities have become increasingly problematic, which are characterized by deteriorating infrastructure, outdated facilities, and an aging population, which together contribute to a range of social and health-related issues.

Previous studies have established a clear link between the quality of the built environment and mental health outcomes. Evans discusses how poor housing conditions, including inadequate lighting, poor ventilation, and structural decay, can exacerbate stress and anxiety among residents (30). Galea et al. further emphasize that living in deteriorating environments can lead to increased incidences of depression, particularly in low-income populations that lack the resources to move to better housing (31).

The inadequacy of facilities in aging communities has also been well documented. Li and Wu highlight that in many of China's older urban neighborhoods, including Danwei communities, the lack of modern amenities such as healthcare services, recreational spaces, and social services severely impacts residents' quality of life (32). This deficiency is particularly acute for the older adults, who are more dependent on local services for their daily needs. The absence of adequate facilities not only limits physical health but also contributes to social isolation, further exacerbating mental health issues.

Social isolation has been identified as a critical factor influencing mental health, particularly in older populations. Cacioppo and Cacioppo discuss the “toxic effects” of perceived social isolation, which can lead to increased risks of depression and anxiety (33). In the context of Danwei communities, where the social fabric has been eroded due to the migration of younger populations and the closure of many original workplaces, the remaining residents often find themselves isolated. This social isolation is compounded by the physical deterioration of the environment, creating a feedback loop that further degrades residents' mental health.

Recent studies on urban renewal have begun to explore the potential benefits of interventions such as micro-renewal in improving both the physical environment and the mental health of residents (34, 35). Micro-renewal, as an innovative approach, focuses on small-scale, community-driven improvements that can enhance living conditions

without the disruption associated with large-scale redevelopment. Zhao et al. provide a comprehensive analysis of micro-renewal projects across China, demonstrating their potential to improve residents' quality of life by addressing both physical and social dimensions of urban living (36). Song et al. clarified the relationship between the development of urban community cultural heritage and the consolidation of local residents' cultural identity (37). Tian et al. explored the role of participatory electronic planning models in old residential area renewal projects (38). Considering that the ultimate goal of renovating old residential areas is to improve the living conditions, health status, and well-being of residents, and achieve sustainable development, evaluating the impact of micro renovation projects on residents is the focus of research (39, 40). Liu and Li established 32-item index for five aspects, including politics, economy, culture, society, and ecology (38). Wang et al. established a 18-item index in terms of the benefits of government, resident, and developer, and constructed a comprehensive evaluation model for decision-making on urban renewal mode selection (39). Herra Pérez et al. developed a spatial decision support system for neighborhood-scale renewal projects which takes the actual situation of old community and the expected long-term resilience into account (40).

While there is substantial literature on the general impacts of urban renewal, there is limited empirical research specifically focusing on the mental health outcomes of micro-renewal in old Danwei communities. Most existing studies either address the physical improvements brought by urban renewal or discuss mental health in broader terms, without linking these two aspects in a comprehensive framework. This study aims to fill this gap by investigating how micro-renewal in old Danwei communities affects residents' mental health. The research question guiding this study is: “How does micro-renewal impact the mental health of residents in old Danwei communities, and what are the key factors that mediate this relationship?”

By addressing this research question, the study aims to contribute to the growing body of knowledge on urban renewal and public health, offering insights that can inform future policy and practice in the renewal of aging urban communities.

3 Methodology

3.1 Data collection

The data collection was conducted in Hengyang, Hunan Province, China. By the end of 2022, there were more than 8.5 million permanent population living in Hengyang, which is the second largest city in Hunan Province. Hengyang is one of the important industrial cities in the central south of China (see Figure 1). Since the reform and opening up in China, many manufacturers have been established in Hengyang. The thriving industry in the 1970s and 1980s had attracted a large population and built massive Danwei residential communities. At present, the communities left over from the planned economy era became outdated, incomplete functional facilities, low per capita land area, and poor environmental quality. However, these old Danwei communities preserve the collective memories of different generations and contain unique cultural values, making them unsuitable for mass demolition and renovation. Therefore, it is urgent to apply micro-renewal to update them. The typical cases of renovations in Hengyang are suitable for studies on the mental health of residents after



micro-renewal. In August 2023, a 1000-on-site questionnaire survey was conducted among all residents of two old Datwei communities in Hengyang, namely, Baizhuozai and Xinkuangcun. Baizhuozai community is the residential area of the former state-owned enterprise, which is classified as Community 1 (C1), and Xinkuangcun community is the residential area of a cable factory and a plastic factory which is classified as Community 2 (C2).

Baizhuozai is a residential area originally built by a former state-owned enterprise. It represents a typical old Datwei community where the majority of the infrastructure has significantly aged and the social structure is relatively homogeneous. The community's residents largely consist of retired workers who have lived in the area for decades, making it an ideal case to study the impacts of micro-renewal on a population that is deeply attached to its living environment and highly affected by changes in it. Xinkuangcun, on the other hand, is a residential area associated with a cable factory and a plastic factory, showcasing a different industrial background and a somewhat more diverse social structure. This community, while also an old Datwei community, has experienced different patterns of urban development and resident demographics compared to Baizhuozai. This diversity allows for a comparative analysis of how micro-renewal impacts communities with varying social dynamics and histories.

The questionnaire consists of questions regarding respondents' personal basic information, housing conditions, psychological health assessment, and satisfaction on micro-renewal of the old Datwei communities. The Short Warwick Edinburgh Mental Well-being Scale (SWEMWBS) was used for examining the respondents' mental health [34]. SWEMWBS has been extensively validated and can be used in various regions, languages, and cultural backgrounds, as well as in various built environment projects. The scale has a total of 14 items, with a rating range of 1–5 points for each item. The total score for each item is calculated by adding up the total score (ranging from 14 to 70 points). This study used K-means clustering to input the scores of each item in each sample, and ultimately divided the scores into high, average, and low mental health. Among them, the score range for groups with low mental health levels is "32–51", the score range for groups with average mental health levels is "49–60", and the score range for groups with high mental health levels is "60–70". Respondents' subjective evaluation was estimated by the Likert 5-point scale.

Before the field investigation, seven research assistants were trained to ensure consistency and accuracy in data collection, and how to administer the questionnaire, handle respondents' queries, and record responses accurately. A random sampling method was used to select participants. The sampling frame included all households in the two old Datwei communities, where improvements were made to residential buildings and urban surroundings, ensuring that every resident had a known and non-zero chance of being selected. During the survey, we also got some help from the neighborhood management commission to invite residents to join in the interview. The actors of interviews are shown in Figure 2.

The structured interview was carried out at convenient locations for residents, such as community centers, public spaces, or respondents' homes if they preferred. Each interview takes approximately 20 min. Interviews were conducted face-to-face, with trained interviewers asking standardized questions to evaluate residents' perceptions and mental health outcomes. During the survey, the interviewer explained the questionnaire to the interviewee to ensure they could understand and answer accurately. The total number of households in two communities is 1261 (C1: 938, C2: 323). After a two-week (from 10th to 23rd August 2023) on-site survey, a total of 634 (503 in C1 and 131 in C2) effective questionnaires were collected.

3.2 Entropy-TOPSIS

The effectiveness of micro-renewal is mainly manifested in improving living conditions, optimizing outdoor environments, enhancing public services, and optimizing infrastructure. To analyze its effect on mental health of residents in depth, this study constructs an evaluation model with indicators regarding satisfaction on six key renewed components, including night lighting, facility, public space, safety, style and service. In this model, each component is characterized with specific measured items, which are shown in Table 1. In addition, the level of satisfaction of residents toward the improvements of micro-renewal is listed in Table 2.

The method of modeling applied in this study combines Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and



Figure 2
The process of micro-renewal in the two old Dazhuo communities.

Table 2 Satisfaction on the components after micro-renewal

Target layer	Criterion layer	Indicator layer
Satisfaction level	Night lighting	Canal lighting Street lighting
	Facilities	Seating railing Road waterproofing and drainage Road drainage and drainage
	Public space	Private sector and facilities Public activity space Parking space and facilities Landscape
	Security	Gate and access control Monitoring and security Firefighting equipment
	Appearance	Exterior wall painting Residential interior wall painting Road pavement
	Service	Road system Garbage collection

Entropy weight, namely Entropy/TOPSIS. As a multicriteria decision making method, the basic concept of TOPSIS is that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution. The Entropy-TOPSIS uses entropy value to determine the weights of various indicators and calculates the optimal and worst solutions of each evaluation object through TOPSIS. The concept of entropy originates from

Table 3 Satisfaction on the improvements after micro-renewal

Target layer	Indicator layer
Satisfaction level	Improvement in canal environment
	Improvement in thermal environment
	Improvement in air quality
	Improvement in night lighting
	Improvement in daily grocery shopping
	Improvement in services
	Improvement in public space
	Improvement in safety status

thermodynamics and is used to quantify the degree of chaos in a system. It can better reflect the interrelationships between the dimensions of comprehensive satisfaction and agreement. In this study, the weight of indicator is determined by the amount of information it provided. The larger the amount of information, the greater the utility of the indicator in the decision-making process. This method lies in determining the positive ideal solution (D^+) and the negative ideal solution (D^-), and then calculating the geometric distance between each alternative solution and these ideal solutions, characterizing the relative closeness of the evaluation object to the optimal solution, providing an intuitive and quantitative indicator for evaluating the effectiveness of micro-renewal in old Dazhuo communities. The steps are presented as follows:

Step 1 To establish a decision matrix

An evaluation matrix $(x_{ij})_{m \times n}$ consisting of m samples and n evaluation indicators.

$$H = (x_{ij})_{m \times n}, (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (1)$$

$$X = \begin{bmatrix} x_{11} & \dots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mn} \end{bmatrix} \quad (2)$$

where, i is the sample size, and j is the number of indicators. In Equations 1 and 2 of this study, $m=634$, and $n=42$, including 17 indicators of pre-renewal conditions, 17 indicators of the post occupancy evaluation and 8 indicators of evaluation on the improvements after micro-renewal compared to before renewal.

Step 2: To normalize the decision matrix.

The indicators in this study are all positive, so there is no need for forward normalization. The normalized matrix $(z_{ij})_{m \times n}$ is shown in Equations 3 and 4.

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (3)$$

$$Z = \begin{bmatrix} z_{11} & \dots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \dots & z_{mn} \end{bmatrix} \quad (4)$$

Step 3: To calculate information entropy. The calculation formulas are shown in Equations 5–7.

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^m z_{ij}} \quad (5)$$

$$e_j = -k \sum_{i=1}^m p_{ij} \ln(p_{ij}), (j = 1, 2, \dots, n) \quad (6)$$

$$k = \frac{1}{\ln m} \quad (7)$$

where, p_{ij} represents the proportion of the items of the i -th sample under the j -th indicator, e_j represents the information entropy of the j -th indicator.

Step 4: To calculate entropy weight. The calculation formula Equation 8 is presented as follows:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (8)$$

where, w_j is the entropy weight of the j -th indicator.

Step 5: To define the maximum and minimum values of evaluation indicators.

According to the normalization matrix Z , the optimal and worst solutions for each evaluation indicator, the optimal solution vector

and the worst solution vector are, respectively, represented in Equations 9–12, which are shown as:

$$Z^+ = (Z_1^+, Z_2^+, \dots, Z_n^+) \quad (9)$$

$$Z^- = (Z_1^-, Z_2^-, \dots, Z_n^-) \quad (10)$$

$$Z_i^+ = \max\{Z_{1i}, Z_{2i}, \dots, Z_{mi}\}, (i = 1, 2, \dots, n; j = 1, 2, \dots, n) \quad (11)$$

$$Z_i^- = \min\{Z_{1i}, Z_{2i}, \dots, Z_{mi}\}, (i = 1, 2, \dots, n; j = 1, 2, \dots, n) \quad (12)$$

where, Z_j^+ is the maximum value of the j -th evaluation indicator, and Z_j^- is the minimum value of the j -th indicator.

Step 6: To calculate the weighted geometric distance between the evaluation object and the maximum and minimum values. The calculation formulas are shown in Equations 13 and 14.

$$D_i^+ = \sqrt{\sum_{j=1}^n w_j (Z_i^+ - z_{ij})^2} \quad (13)$$

$$D_i^- = \sqrt{\sum_{j=1}^n w_j (Z_i^- - z_{ij})^2} \quad (14)$$

where, Z_{ij} is the normalized value of the i -th individual for the j -th evaluation indicator, Z_j^+ is the maximum normalized value of all the j -th evaluation indicators, Z_j^- is the minimum normalized value of all the j -th evaluation indicators, and w_j is the entropy weight of the j -th evaluation indicator.

Step 7: To calculate relative closeness (overall satisfaction). The calculation formula is shown in Equation 15.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (15)$$

where, the range of C_i values is $[0, 1]$, and the closer it is to 1, the closer the evaluation object is to the optimal level, indicating a higher overall satisfaction of the sample. On the contrary, the closer to 0, the closer the evaluation object is to the worst level, indicating a lower overall satisfaction of the sample.

3.3 Multinomial logit model

The multinomial logit model (MNL) has been widely applied in multiple disciplines, including transportation, medicine, architecture, urban and rural planning, etc. MNL was used in this study to explore the influencing factors of positive mental health.

assessment. The dependent variable classification is expressed in Equation (16):

$$y_i = \begin{cases} 1, & \text{if } y_i^* \geq \mu_j \\ 2, & \text{if } \mu_{j-1} < y_i^* < \mu_j \\ \vdots \\ J, & \text{if } y_i^* \leq \mu_{J-1} \end{cases} \quad (16)$$

where μ_j is the threshold point of y_i^* . The link function is the logit transformation. In this study, $J=3$ since each result of SWIMWBS was the dependent variable (3-level: high, average, and low). The link function is the logit transformation (16), which is expressed as Equation (17):

$$\text{logit}^{-1}(y_i^*) = \frac{1}{1 + \exp(-y_i^*)} \quad (17)$$

The probability $P = (y_i = j)$ for the i th individual being in the j th category is given by Equation (18):

$$P(y_i = j) = \frac{\exp(\beta_j X_i)}{1 + \sum_{k=1}^{J-1} \exp(\beta_k X_i)} \quad (18)$$

where j ranges from 1 to $J-1$ (in this case $J=3$), β_j are the coefficients for the j th outcome, and X_i is the vector of independent variables for the i th individual. 16 independent variables are respondents' socio-demographic information, housing condition, and satisfaction evaluations. By conducting Chi-square tests on the dependent and independent variables, we removed variables that were not correlated.

Hausman test is applied for examining the independence (irrelevant alternatives (IIA)) of MNL, a step-by-step description of how we conduct it is shown as follows:

1. Estimate the multinomial logit model using all the available alternatives and obtain the coefficient estimates $\hat{\beta}_{full}$ and the variance-covariance matrix $\text{Var}(\hat{\beta}_{full})$.
2. Estimate the multinomial logit model by excluding one of the alternatives and obtain the coefficient $\hat{\beta}_{restricted}$ and the variance-covariance $\text{Var}(\hat{\beta}_{restricted})$.
3. The test statistic is based on the difference between the estimated coefficients from the full model and the restricted model. The formula for the Hausman test statistic (19) is Equation (19):

$$H = \left(\hat{\beta}_{full} - \hat{\beta}_{restricted} \right)' \left[\text{Var}(\hat{\beta}_{full}) - \text{Var}(\hat{\beta}_{restricted}) \right]^{-1} \left(\hat{\beta}_{full} - \hat{\beta}_{restricted} \right) \quad (19)$$

4. Under the null hypothesis that the IIA assumption holds, the test statistic H follows a chi-squared distribution with degrees of freedom (df) equal to the number of coefficients estimated β . If the test statistic is significantly large, the null hypothesis is rejected, indicating that the IIA assumption may not hold.

4 Results and discussion

4.1 Descriptive statistics

According to Table 2, there are slightly more females than males who joined in survey. The majority of respondents are aged from 51 to 70, married and healthy and have no problem with daily activities independently. The retired group dominates the sampled population, accounting for 81.1% of the respondents. 33.9% respondents are in the income range of 500–1,000 US dollars. Many respondents live with their partners. Close to 90% respondents have lived in this community for more than 15 years, indicating a high level of familiarity and stability with the community. Most of respondents mainly take buses and subways for daily travel as the public transportation plays an important role in urban mobility. In terms of outdoor activity duration, the residents who spend more than 60 min per day accounts for 69.7% of respondents, indicating that they have certain time arrangements for outdoor activities and pay attention to maintaining a positive lifestyle.

Table 3 shows the housing information of the respondents. The results of subjective evaluation of respondents on the improvements after micro-renewal of old Danwei communities are shown in Table 4. The results of SWIMWBS are shown in Table 4.

4.2 Results of entropy-TOPSIS

The weights of various indicators of satisfaction on micro-renewal of old Danwei communities are shown in Table 5. And the weights of various indicators of evaluation on improvements through micro-renewal of old Danwei communities are listed in Table 6.

The results of comparative analysis regarding the pre and post evaluation of two old Danwei communities is shown in Table 6, where C1B and C2B denote the evaluation before micro-renewal in C1 and C2, respectively. C1A and C2A denote the condition after micro-renewal in C1 and C2, respectively. IR means the increase rate. Whether before or after micro-renewal, the overall satisfaction of respondents in C2 is higher than respondents in C1. Moreover, the average values of satisfaction on all indicators in C2 are higher than those in C1. The micro-renewal in both communities have achieved significant improvement in respondents' satisfaction on street lighting and road pavement. In addition, more satisfaction on the improvement of maintenance and security has been found in the residents of C1. However, the improvement of gate and access control is not significant in micro-renewal of both communities. Although the overall level of satisfaction of respondents from C1 is lower than those from C2, respondents from C1 has a higher agreement with the improvement rate in many aspects than the respondents from C2. A higher improvement rate in the corridor lighting, gate and access control, and road pavement are estimated

TABLE 2 The descriptive statistics of respondents' personal basic information

Variable	Class	Frequency	Percentage (%)
Gender	Male	244	46.4
	Female	300	53.6
Age	≤20	66	11.8
	21–30	144	26.4
	31–40	212	39.2
	41–50	107	19.4
	≥51	56	10.1
Marital status	Divorced	32	5.7
	Widow	101	18.4
	Unmarried	71	12.7
	Married	470	84.2
Health condition	Minor issues	36	6.4
	Commonly	107	19.4
	Good	499	90.2
Physical mobility	Difficulties	3	0.5
	Commonly	81	14.6
	Good	470	84.9
Work status	On the job	105	18.8
	Doing business	9	1.6
	Retiree	114	20.7
	Other	6	1.0
Monthly income (USD)	≤200	274	49.7
	200–1,000	302	54.5
	1,000–1,500	14	2.5
	1,500–2,000	1	0.2
	>2000	1	0.2
Composition of neighborhood	Living alone	186	33.6
	Partner	821	148.4
	Partner and Parents	3	0.5
	Partners and children	90	16.2
	Children	48	8.6
	Parents	31	5.5
	Other	21	3.8
	Other	21	3.8
Residential time in this community (year)	<5	3	0.5
	5–9	25	4.5
	10–19	18	3.2
	20–29	29	5.2
	≥30	967	174.4
Daily travel methods	Bicycle	4	0.7
	Motorcycle	99	17.8
	Public Transportation subway	495	89.5
	Taxicab/taxi/other service	2	0.3
	Private car	74	13.3

(Continued)

TABLE 3 (Continued)

Variable	Class	Frequency	Percentage (%)
Outdoor activity time (min/day)	≤20	11	1.9
	21–30	47	8.4
	31–40	48	8.7
	41–60	66	11.8
	>60	442	79.3

TABLE 4 The housing information of respondents

Variable	Class	Frequency	Percentage (%)
Housing area (m ²)	10–30	98	17.5
	30–50	100	18.0
	50–70	120	21.6
	70–90	96	17.2
	90–120	57	10.1
Housing floors	1	185	33.4
	2	172	30.8
	3	198	35.6
	4	101	18.1
	5	22	3.9
Number of bedrooms	1	87	15.5
	2	171	30.7
	3	26	4.6
Number of bathrooms	1	112	20.1
	2	2	0.3
	3	28	5.0
Number of balconies	1	108	19.4
	2	104	18.7
	3	2	0.3
Tenure	Owning land	166	29.9
	Lease	28	5.0
	Other	7	1.2
Housing type	Single-story apartment	122	21.9
	Other	1	0.1

by respondents from C2 than C1. The result indicates that the micro-renewal measures in C1 is more effective in terms of residents' satisfaction.

As shown in [Table 15](#), mean satisfaction level of residents on all indicators is higher in C2 than C1. The heterogeneity of satisfaction on micro-renewal is depicted in [Figure 5](#). The results indicate that the evaluations of respondents' satisfaction are heterogeneous in terms of eight characteristics, including age, education level, employment, health condition, income, travel mode, apartment condition and tenure. Different age groups have varied levels of satisfaction with the micro-renewal. Older residents may place higher importance on improvements in safety and accessibility, while younger residents might prioritize enhancements in public spaces and recreational facilities. Satisfaction levels differ across education levels as well.

TABLE 3 The evaluation on the improvements of old Dazhai communities after micro-renewal

Variable	Class	Frequency	Percentage (%)
Aesthetics environment	Strongly disagree	7	2.1
	Disagree	31	9.4
	Slightly disagree	206	61.5
	Neutral	224	64
	Slightly agree	100	29.8
	Agree	27	8.2
Residential environment	Strongly agree	7	2.1
	Strongly disagree	4	0.8
	Disagree	17	5.1
	Slightly disagree	269	82.3
	Neutral	202	60.8
	Slightly agree	116	34.3
Life quality	Agree	28	8.1
	Strongly agree	4	0.9
	Strongly disagree	7	0.2
	Disagree	18	5.6
	Slightly disagree	81	24.6
	Neutral	234	69.1
Neighborhood lighting	Slightly agree	227	68.9
	Agree	31	8
	Strongly agree	1	0.3
	Strongly disagree	0	0.0
	Disagree	20	6.5
	Slightly disagree	49	14.7
Neighborhood safety	Neutral	103	31.1
	Slightly agree	206	61.5
	Agree	203	60.8
	Strongly agree	5	0.9
	Strongly disagree	1	0.2
	Disagree	17	5.1
Neighborhood shopping	Slightly disagree	44	13.2
	Neutral	148	44.7
	Slightly agree	204	61.2
	Agree	178	53.3
	Strongly agree	17	5.2

4.3 Results of multinomial logit model

The goodness of fit index of MNL is estimated. The McFadden Pseudo R-squared is 0.374 that indicates a high degree of fit of the model. The H0 hypothesis, in the context of the Hausman test for the MNL model, refers to the IIA assumption, which means the choice between any two categories should be independent of the other available choices. This property is crucial for the validity of the MNL model. In the IIA hypothesis test, the result of Hausman test (see

TABLE 4 The results of respondents' mental health assessments

Dependent variable	Frequency	Percentage (%)
Low level of mental health	81	15
Average level of mental health	240	44.1
High level of mental health	246	46.7

Table 13) indicates that removing one option does not affect the consistent estimation of other options, i.e., does not affect the probability of other choices. This means that MNL does not reject the IIA hypothesis. Fitting the data of this study with MNL is reasonable.

As shown in Table 13, the predicted values of 463 samples are equal to the actual values, and the model has an accurate prediction rate of 73.34%, which indicates high accuracy of this model in fitting the samples.

The estimation results of MNL are shown in Table 13. Respondents with a monthly income greater than 6,000 are most likely to have high level of mental health. The probability of respondents with average mental health is relatively low when they dissatisfied on corridor wall painting of micro-renewal. The respondents are very satisfied with road pavement, and very satisfied with parking lots and facilities. Among them, the probability of a group with a monthly income greater than 6,000 having a high level of positive mental health is 4.9 times higher than that of a group with a monthly income less than 1,000. The probability of positive psychological health levels being 99.6, 3.5, and 10.1 times higher for groups who are very dissatisfied, dissatisfied, or satisfied with the unit gate and access control compared to neutral groups, respectively. The probability of being satisfied, satisfied, and very satisfied with road pavement may be 11.7, 8.2, and 14.3 times higher than that of the neutral group in terms of positive mental health. The group that is very satisfied with the renovation of parking lots and facilities may have a 10.9 times higher probability of positive mental health than the neutral group.

As shown in Table 14, the probability of being low level of mental health increase by 16.6% if the respondents are over 60-year old. Aging significantly decreases the mental health of residents living in the old Dazhai community. The relatively higher education level leads to higher probability of respondents to be high level of mental health. The respondents with good physical health are more likely to being high level mental health. The respondents having greater than 6,000-yuan monthly income are 19.0% increase to the possibility of being high mental health level.

The possibility to be lower level of mental health is increased by 8.3% if respondents who are more satisfied with exterior wall painting. The probability of high-level mental health increases by 15.3% if respondents dissatisfied with corridor lighting. The probability to have high level of mental health increased by 30.8% if respondents satisfy with the gate and access control after micro-renewal. The satisfaction on road pavement and road system will also increase the probability of high-level mental health. However, the dissatisfaction with fitness venues and facilities results in more likely to be lower level of mental health increased. The probability of being high level of mental health increases by 25.5% if respondents are satisfied with the parking lot and facilities.

The sensitivity analysis was performed, that highlights the importance of demographic and health-related factors in predicting

TABLE 7. Weights of satisfaction regarding various micro-renewal components.

Target layer	Criterion layer	Indicator layer	Entropy	Weight	Sort
Satisfaction	Night lighting (3.00%)	Corridor lighting	0.9922	0.02%	1
		Street lighting	0.9919	2.41%	2
		Scenic lighting	0.9965	0.25%	3
	Facilities (11.25%)	Roof waterproofing and damage	0.9910	0.25%	4
		Road damage and sewage	0.9930	0.73%	5
		The gas and water control	0.9979	2.45%	12
	Security (8.00%)	Monitoring security	0.9965	0.12%	7
		Firefighting equipment	0.9904	0.16%	14
		Entrance wall painting	0.9973	0.71%	13
	Appearance (10.00%)	Corridor wall painting	0.9967	0%	9
		Road pavement	0.9918	0.13%	6
		Road system	0.9930	0.73%	4
	Garbage (2.25%)	Garbage collection	0.9970	0.09%	10
		House service and facilities	0.9992	0.4%	16
		Public activity space	0.9985	0.13%	17
	Public space (8.00%)	Parking lot and facilities	0.9980	0.45%	15
		Greenery	0.9984	0.04%	18

TABLE 8. Weights of indicators for improvements in micro-renewal of old Dazhai communities.

Target layer	Indicator layer	Entropy	Weight	Sort
Improvement	Acoustic environment	0.9972	10.19	6
	Thermal environment	0.9973	10.06	5
	Air quality	0.9978	0.58	8
	Nighttime lighting	0.9972	0.30	7
	Grocery shopping	0.9919	11.13	2
	Services	0.9992	10.42	3
	Public spaces	0.9964	11.00	4
	Safety status	0.9974	11.04	1

mental health outcomes. Males have a slightly higher probability of low mental health compared to females. As age increases, the probability of low mental health increases. Individuals who are divorced have higher probability of high mental health against those who are married, unmarried, or widowed. Moreover, respondents with higher education levels, better health status are associated with higher probabilities of high mental health in old Dazhai community. It suggests that interventions targeting these factors could potentially improve mental health of residents in old Dazhai communities.

4.4 Discussion

The results of this study provide important insights into the factors influencing residents' satisfaction and mental health in the context of micro-renewal in old Dazhai communities. The

Entropy-TCPSUS analysis highlighted that improvements in services, road systems, and grocery shopping were the most critical components contributing to overall satisfaction with the micro-renewal. The highest weights were assigned to these components indicate that functional infrastructure and basic services are fundamental to enhancing the quality of life in aging communities. These findings align with existing literature on urban renewal, which emphasizes that physical improvements in infrastructure are crucial for resident satisfaction and well-being (13, 10).

The emphasis on services and infrastructure improvements, particularly in areas like garbage collection and road systems, suggests that residents prioritize practical, everyday necessities. These components not only address basic needs but also enhance the overall livability of the community, which is critical for fostering a sense of security and stability among residents. Public spaces and safety measures were also significant, reflecting the importance of community interactions and a safe living environment in supporting mental health. This resonates with theories of environmental psychology, which posit that well-maintained, safe environments contribute to reduced stress and improved mental well-being (37).

The findings from MNL model indicate that socio-demographic factors such as age, income, and health condition play a significant role in determining residents' mental health outcomes. Older residents and those with higher incomes were more likely to report better mental health, suggesting that financial stability and life experience may provide a buffer against the stressors associated with aging in a deteriorating environment. This finding supports the life course perspective, which suggests that individuals' health trajectories are shaped by a combination of socio-economic factors and environmental exposures over time (38).

The differentiated impacts of micro-renewal on various demographic groups underscore the need for tailored interventions to

TABLE 9 Comparison of satisfaction before and after micro-renewal in two old Danwei communities.

Indicator layer	C1B	C1A	IR (%)	C2B	C2A	IR (%)
Complete lighting	1.53	1.29	40.69	1.59	1.11	41.62
Street lighting	2.46	1.71	132.20	1.73	1.07	114.88
Manhole-railing	2.46	4.30	61.78	1.05	4.71	54.44
Road waterproofing and drainage	2.31	1.94	71.66	3.16	4.86	58.86
Road drainage and sewage	2.41	4.36	81.28	1.82	1.19	71.01
Exterior wall painting	2.72	4.76	75.07	1.89	4.86	67.67
Gate and fence control	2.98	3.52	12.69	1.12	4.03	28.56
Firefighting equipment	2.63	4.34	61.75	1.32	4.62	41.29
Monitoring system	2.44	4.97	101.56	1.02	1.12	95.44
Corridor wall painting	2.67	4.97	87.49	1.48	4.37	62.79
Road system	2.52	4.91	91.00	2.84	4.73	78.77
Garbage collection	2.62	3.14	96.12	1.24	1.44	67.54
Road pavement	2.37	3.91	145.10	2.41	4.08	102.22
Gazebo	3.14	4.89	58.02	1.80	4.09	37.89
Public activity space	3.18	5.05	58.78	1.25	3.08	56.10
Pitless toilets and facilities	3.12	3.12	61.87	1.92	4.71	41.52
Parking lots and facilities	2.84	4.91	72.94	1.09	1.04	63.37
Overall satisfaction (Standardized)	0.75	0.59	67.00	0.40	0.64	56.92

TABLE 10 The mean satisfaction and improvements of micro-renewal in two old Danwei communities.

Component	C1	C2
Visually environment	4.81	4.89
Thermal environment	4.71	4.02
Air quality	5.24	4.39
Noise lighting	5.40	3.71
Gazebo shopping	4.95	3.03
Services	4.14	4.07
Public space	5.20	4.22
Safety status	5.44	3.38
Overall satisfaction (Standardized)	0.60	0.43

old Danwei community renewal. The study suggests that while infrastructural improvements benefit all residents, specific demographic groups may have unique needs that require targeted approaches. For example, older residents may benefit more from improvements in accessibility and safety, while younger populations might prioritize recreational facilities and modern conveniences. This aligns with the concept of "proportionate universalism," which advocates for universal interventions that are scaled according to the level of disadvantage [39].

The findings suggest that urban renewal strategies in old Danwei communities should prioritize inclusive planning processes that actively engage diverse community members. By involving residents in the planning and decision-making processes, micro-renewal projects can better address the specific needs and preferences of

different demographic groups, ultimately leading to higher satisfaction and better mental health outcomes. This participatory approach is particularly important in the context of micro-renewal, where the scale of intervention allows for more community-driven decision-making [40].

The findings from both models highlight the critical role of infrastructure improvements in enhancing residents' satisfaction and mental health. Specifically, the high weights and significant variables related to road system, lighting, and public safety suggest that these elements are vital for improving the quality of life in the old Danwei communities. The influence of socio-demographic factors on mental health outcomes underscores the need for tailored approaches in old Danwei community renewal. Different demographic groups have varying needs and responses to environmental changes, as evidenced by the differentiated impacts observed in this study. It is highly recommended that adopting inclusive planning processes and engaging diverse community members when it comes to the old community renewal. Tailoring interventions to meet the specific needs of different demographic groups, such as providing accessible public spaces for older residents and enhancing recreational facilities for younger population, can maximize the benefits of community renewal.

The findings suggest that urban renewal strategies in old Danwei communities should prioritize inclusive planning processes that actively engage diverse community members. By involving residents in the planning and decision-making processes, micro-renewal projects can better address the specific needs and preferences of different demographic groups, ultimately leading to higher satisfaction and better mental health outcomes. This participatory approach is particularly important in the context of micro-renewal, where the scale of intervention allows for more community-driven decision-making.

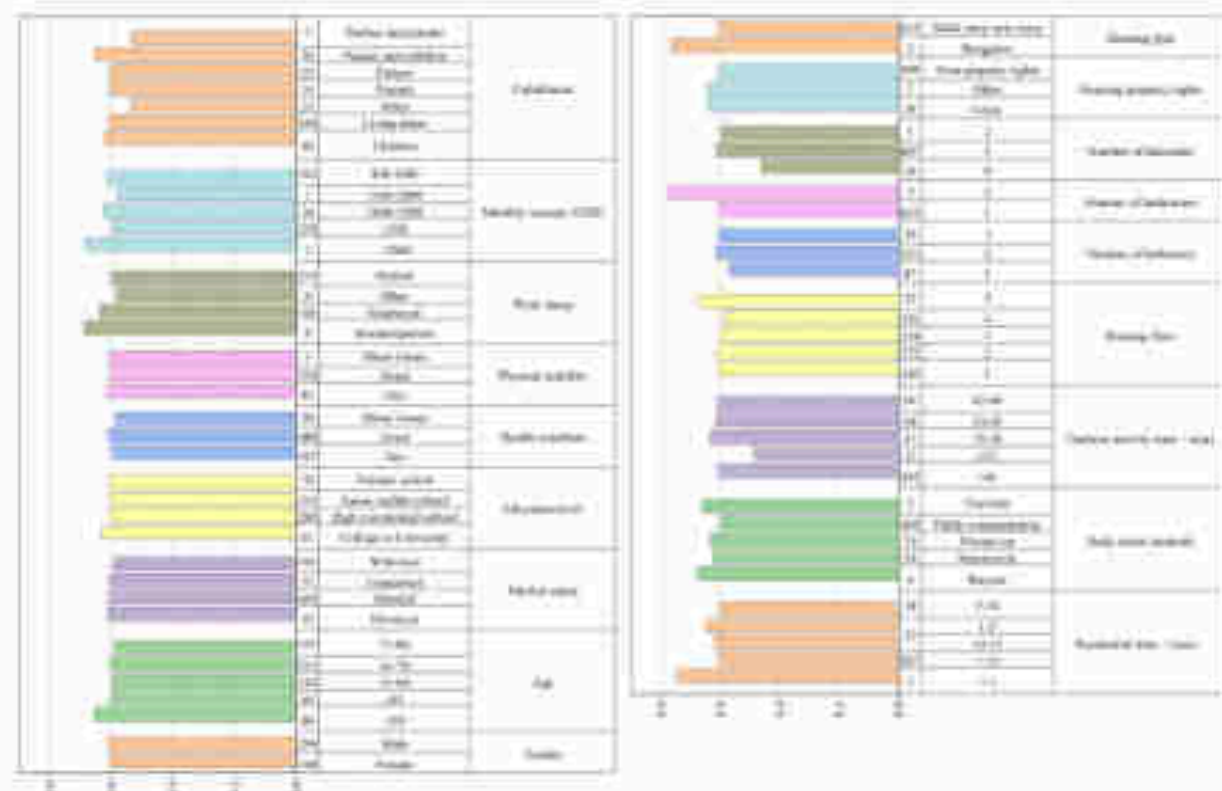


FIGURE 5
The heterogeneity of micro-renewal satisfaction on the micro-renewal.

TABLE 11 Hausman test results of the MML.

Divided	Chi-square	df	$p > 1\%$ -square	Evidence
0	-0.000	6	1.000	No H0
1	-0.000	4	1.000	No H0
2	-0.002	3	1.000	No H0

H0 hypothesis: $U_0(U_1|U_2|U_3) = 0$ (where U_i are independent of other alternatives)

TABLE 12 Prediction accuracy of the MML.

Count	Frequency	Percentage (%)
-2	13	2.65
-4	80	15.72
6	465	79.34
7	67	9.84
2	8	0.85

5 Conclusion

This study examines the impact of micro-renewal on the mental health of residents in old Danwei communities in Hengyang, China. The findings indicate that socio-demographic characteristics and behavior factors significantly influence the mental health of residents. The satisfaction with various components of micro-renewal, such as road pavement, unit gate and access control, and parking facilities,

plays a crucial role in determining the mental health levels of residents. High satisfaction levels in these areas are associated with better mental health outcomes.

The research highlights the importance of tailored approaches in community renewal to meet the specific needs of different demographic groups. Engaging diverse community members and adopting inclusive planning processes are essential for maximizing the benefits of neighborhood renewal. The study also emphasizes the need for longitudinal empirical research to better understand the long-term impact of micro-renewal on mental health.

Several limitations primarily revolve around data collection, modeling assumptions, and generalizability need to be addressed. Although there is a key assumption that the results from Hengyang could be broadly applicable to other Danwei communities in different cities in China. This assumption may not hold if other regions have significantly different socio-economic dynamics, urban policies, or cultural contexts. Hence, our future study will include multiple cities with diverse characteristics to enhance the generalizability of the findings. The cross-sectional data used in this study captures no information regarding the long-term impact of micro-renewal on mental health and changes over time.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Table 17 Results of the WLS

Variables		Coefficient	
		Low	High
Age (Control group: Age < 50)	51–60	0.011	0.007
	61–70	0.017	−0.007
	71–80	0.076	−0.018
	≥ 81	1.307*	−3.179*
Education level (Ref: Control group: Illiterate/primary school)	Junior school	−0.066	0.009
	High school or vocational school	−0.006*	0.006*
	College or university	0.000	0.000
Health condition	Good	−0.006	0.710*
Physical ability	Good	−0.052	−0.009
Monthly income (M) (Control group: M < 300 USD)	300–1,000 USD	−0.100	0.100
	> 1,000 USD	0.043	1.265**
Completion of children's (Control group: living alone)	Partner	−0.007	0.31*
	Big family	−0.010	0.70*
Outdoor activity time (OAT) (Control group: OAT < 10 min/day)	11–30 min/day	−1.120	−0.013
	31–45 min/day	−1.568	−0.20
	46–60 min/day	−1.209	0.013
	> 60 min/day	−2.214*	0.120
Relative well-being (Control group: neutral)	Very dissatisfied	−1.000	12.000
	Dissatisfied	−0.000	−2.000***
	Relatively dissatisfied	0.75	−0.57
	Relatively satisfied	0.000*	−0.20
	Satisfied	0.011	−1.100**
Relative well-being (Control group: neutral)	Very satisfied	0.120	0.01
	Very dissatisfied	−0.000	12.700
	Dissatisfied	−0.000	0.175
	Relatively dissatisfied	0.000	0.100
	Relatively satisfied	−1.140***	−1.190***
Relative well-being (Control group: neutral)	Satisfied	−0.110	−0.007
	Very satisfied	0.015	−0.200
	Very dissatisfied	−0.270	−0.00
	Dissatisfied	−1.140**	0.001
	Relatively dissatisfied	−1.070*	0.00
Relative lighting (Control group: neutral)	Relatively satisfied	−0.000	0.017
	Satisfied	0.01	0.70
	Very satisfied	−1.100	1.072
	Very dissatisfied	1.00	0.00***
Relative lighting (Control group: neutral)	Dissatisfied	−0.07	1.170**
	Relatively dissatisfied	0.000	0.000
	Relatively satisfied	−0.000	−0.00
	Satisfied	0.174	1.100**
	Very satisfied	0.770	1.100

(Continued)

TABLE 13 (Continued)

Variables		Coefficient	
		Low	High
Road pavement (Control group: neutral)	Very dissatisfied	17.302	4.879
	Dissatisfied	7.391	2.366
	Relatively dissatisfied	0.575	0.526
	Relatively satisfied	0.092	2.461***
	Satisfied	-0.199	2.109***
Road greening (Control group: neutral)	Very satisfied	-0.711	2.672***
	Very dissatisfied	-23.941	14.466
	Dissatisfied	1.344	-1.368*
	Relatively dissatisfied	1.629**	-0.204
	Relatively satisfied	0.637	-2.123***
Public activity space (Control group: neutral)	Satisfied	0.69	-2.266***
	Very satisfied	2.328	-1.127**
	Dissatisfied	0.332	0.036
	Relatively dissatisfied	-0.227*	-0.324
	Relatively satisfied	-0.227	-0.525
Public activity space (Control group: neutral)	Satisfied	-0.908	-0.288
	Very satisfied	-0.263	-2.318***
Fitness venues and facilities (Control group: neutral)	Dissatisfied	14.603	14.324
	Relatively dissatisfied	-0.49	-0.425
	Relatively satisfied	-0.101	-0.013
	Satisfied	0.238	0.272
	Very satisfied	-1.132	-0.014
Banking venues and facilities (Control group: neutral)	Dissatisfied	-0.979	-10.769
	Relatively dissatisfied	-1.000*	-1.917***
	Relatively satisfied	-0.436	0.238
	Satisfied	-0.123	0.27
	Very satisfied	0.265	2.396***
Constant		2.588	-1.294

***p < 0.01, **p < 0.05, *p < 0.1

Ethics statement

The studies involving humans were approved by Academic Ethic Committee of School of Architecture and Art, Central South University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

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TABLE 14 The marginal effects in MNL.

Variable		Low	Average	High
Age (reference) (Control group: ≤ 40)	41–49	0.040	−0.036	−0.009
	50–59	0.024	−0.028	−0.023
	60–69	0.023	−0.02	−0.012
	≥ 70	0.166**	0.023	−0.001**
Education level (Control group: primary school)	Junior high school	−0.029	−0.014	0.006
	High school, vocational school	−0.027**	−0.007	0.140**
	College or university	0.015	−0.067	0.02
Health condition	Good	−0.066*	−0.042	0.106**
Physical activity	Good	−0.014	0.10	−0.09
Monthly income (Control group: 2000)	1000–4,000	−0.016	−0.012	0.026
	≥ 4,000	−0.026	−0.064*	0.140**
Competition of substitutes (Control group: strong alone)	Partner	−0.076**	0.041	0.065
	Big family	−0.067	−0.01	0.107
Garden activity rate (Control group: 13)	13–19	−0.120	0.171	−0.043
	20–25	−0.101	0.146	0.045
	26–30	−0.13	0.065	0.125
	≥ 31	−0.204*	0.140	0.110
Encore wall painting (Control group: neutral)	Very dissatisfied	−0.100	−0.120	0.472
	Dissatisfied	−0.066	0.152***	−0.514***
	Relatively dissatisfied	0.061	0.02	−0.102
	Relatively satisfied	0.083**	−0.013	−0.003
	Satisfied	0.040	0.109*	−0.107**
	Very satisfied	0.006	−0.106	−0.082
Corridor wall painting (Control group: neutral)	Very dissatisfied	−0.174	−0.275	0.669
	Dissatisfied	−0.109	0.021	0.106
	Relatively dissatisfied	0.062	−0.02	0.018
	Relatively satisfied	−0.075*	0.196***	−0.122***
	Satisfied	−0.008	0.107*	−0.004
	Very satisfied	0.044	0.026	−0.008
Corridor lighting (Control group: neutral)	Very dissatisfied	−0.108	0.419	0.160
	Dissatisfied	−0.125***	−0.01	0.170**
	Relatively dissatisfied	−0.116***	0.040	0.072
	Relatively satisfied	−0.029	−0.06	0.040*
	Satisfied	−0.021	−0.071	0.040*
	Very satisfied	−0.191	−0.049	0.232
Dirt gate and access control (Control group: neutral)	Very dissatisfied	−0.211**	−0.264***	0.405***
	Dissatisfied	−0.036	−0.126*	0.185***
	Relatively dissatisfied	0.023	−0.011	0.067
	Relatively satisfied	−0.009	0.041	0.013
	Satisfied	−0.074	−0.153**	0.106***
	Very satisfied	0.025	−0.177	0.158

(Continued)

TABLE 14 (Continued)

Variable	Level	Average	High
Road pavement (Control group-control)	Very dissatisfied	0.726	-0.346
	Dissatisfied	0.696	-0.249
	Relatively dissatisfied	0.667	-0.189
	Relatively satisfied	-0.108	0.227**
	Satisfied	-0.107	0.148*
	Very satisfied	-0.144*	0.346***
Road planning for pedestrian and vehicles traffic direction (Control group-control)	Very dissatisfied	-0.080***	-0.293
	Dissatisfied	0.479	0.002
	Relatively dissatisfied	0.146*	-0.044
	Relatively satisfied	0.062*	0.349
	Satisfied	0.123**	0.210***
	Very satisfied	0.256	0.446
Public activity space (Control group-control)	Dissatisfied	0.621	-0.103
	Relatively dissatisfied	-0.178	0.158
	Relatively satisfied	-0.001	0.440
	Satisfied	-0.146	0.094
	Very satisfied	-0.009	0.254*
			-0.249**
Fitness index and facilities (Control group-control)	Dissatisfied	0.403**	-0.277***
	Relatively dissatisfied	-0.368	-0.04
	Relatively satisfied	-0.022	0.352
	Satisfied	0.019	-0.01
	Very satisfied	-0.076	0.489
			-0.012
Parking lots and facilities (Control group-control)	Dissatisfied	0	0.430
	Relatively dissatisfied	-0.008	0.200***
	Relatively satisfied	-0.087	0.201
	Satisfied	-0.002	0.413
	Very satisfied	-0.580	-0.252***
			0.238**

*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. WHO. Urban governance for health and well-being: a step-by-step approach to operational research in cities. Initiative on urban governance for health and well-being. Geneva: World Health Organization; (2023).
2. WHO. Global chapter for well-being. 10th Global conference on health promotion. Geneva, Switzerland (2021).
3. Zhang M, Zhang X, Wu L. The network governance of urban renewal: a comparative analysis of two types of China. *Land Use Policy*. (2023) 129:106448. doi: 10.1016/j.landusepol.2023.106448.
4. Cao R, Sheng Y, Song C. Exploring the drivers of urban renewal through comparative modeling of multiple types in Shenzhen, China. *China*. (2023) 137:104284. doi: 10.1016/j.china.2023.104284.
5. Yang Q, Zhang C. How does the renewal of urban villages affect the reversed villages' subjective well-being? A case study in Wuhan, China [article]. *Urban Stud*. (2023) 12:1347. doi: 10.1177/0969778123118147.
6. Egan M, Kuznetsov A, Kuznetsov S, Choi A, Lowen E, Tamschall C. Proportional satisfaction in practice? A quasi-experimental study (QWES) of a UK neighborhood renewal programme's impact on health inequalities. *See Soc Med*. (2018) 132:41–9. doi: 10.1016/j.socmed.2018.01.028.
7. Krallier E, Lathow M, Mann T, Kuo D, Franklin J, Lee M, et al. Building healthy community environments: a public health approach. *Public Health Rep*. (2019) 135:107–435. doi: 10.1177/1093354919858094.
8. Ma Y, Yang H, Li M, Liu Y. Towards the healthy community: residents' perceptions of integrating urban agriculture into the old community urban transformation in Guangzhou, China. *Urban For*. (2020) 12:8034. doi: 10.3390/uf123034.
9. Teng M, Sun L, Zhang H, Kou N, Feng H, Li Q. The impact of multi-quality renewal elements of residence on the subjective well-being of the older adults: a case study of Dalian [article]. *Resour Res Urban Manag*. (2023) 16:761–80. doi: 10.2147/RRUM.S401982.
10. Zhu S, Li D, Peng B, Gu T, Zhu J. AHP-TOPSIS-based evaluation of the creative performance of multiple neighborhood renewal projects: A case study in Nanjing, China. *Science for Total Environ*. (2023) 85:4545. doi: 10.1016/j.scitotenv.2023.174545.
11. Chen J, Chen S, Landry PF. Migration, environmental hazards, and health outcomes in China. *See Soc Med*. (2017) 10:87–97. doi: 10.1016/j.socmed.2017.12.003.
12. Bricker CJ, Maahs-Yoda KA, Schell H, Kinney KA, Lowry CA, Hirschfeld TL, et al. A brief review on the mental health for select elements of the built environment. *Urban Built Environ*. (2021) 16:152–60. doi: 10.1177/1408223220989601.
13. Galar S, Nieuw J, Radwanian S, Wallace J, Vlahov D. Urban built environments and depression: a neighborhood analysis. *J Environ Community Health*. (2003) 9:822–7. doi: 10.1177/1098310303090044.
14. Stafford BE, Charlton T, Hammett L. Association between fear of crime and mental health and physical functioning. *Am J Public Health*. (2007) 97:2076–81. doi: 10.2195/AMPH.2006.96238.
15. Li H, Wu H. Residential Satisfaction in China's Informal Settlements: A Case Study of Beijing, Shanghai, and Guangzhou. *Urban Geogr*. (2013) 34:413–49. doi: 10.1080/02723638.2012.728894.
16. Gecaspe JT, Gecaspe S. Social relationships and health: the mediating effect of perceived social isolation. *Am J Geriatr Psychol*. (2018) 8:36–72. doi: 10.1111/ajg.12887.
17. Zhang B, Xiang Y, Liu H, Igo S, Schreier M. A comprehensive bibliometric analysis of urban renewal research during 1912–2022. *Building*. (2023) 14:2826. doi: 10.3390/buildings14112826.
18. Tu W, Lu M. Development of neighborhood renewal for migrants through case study for middle-income households in New Village Beijing. *Korea J Comput Graph Sci*. (2017) 12:191–241. doi: 10.1007/s00370-017-0067.
19. Kuznetsov A, Ghedi S, Mann T, Egan M. Urban regeneration and mental health: investigating the effects of area-based intervention using a modified version of tree analysis with alternative outcome measures. *Health Place*. (2020) 61:102382. doi: 10.1016/j.healthplace.2019.102382.
20. Singhose A, Wong A, van Hattum T, Doresten M, van den Brink C, Elms JJ, et al. The infrastructure profit from integrating a public health focus in urban renewal programmes? A Dutch case study. *Health Place*. (2022) 17:102790. doi: 10.1016/j.healthplace.2022.102790.
21. Molyneux A, Marston A, Borell C, Mahon D, Rodriguez-Lara JL, Greenfield J, et al. Exploring complex causal pathways between urban renewal, health and health inequalities using a theory-driven scoping approach. *See Soc Med*. (2015) 124:294–78. doi: 10.1016/j.socmed.2014.11.009.
22. Soteriou K, Marsh JL, Soteriou BD. Community-initiated urban development: sociological literature. *J Urban Health*. (2007) 84:8–28. doi: 10.1007/s11245-006-9128-8.
23. Zhuo C, Su X, Zhang J, Li H, Wu B. Neighborhood micro-renewal: a perspective of prior in China. *Ergonomics*. (2021) 64:1015–30. doi: 10.1080/00140139.2021.1910900.
24. Zhuo Y, Su C. Urban renewal without gentrification: toward dual goals of neighborhood revitalization and community preservation? *Urban Geogr*. (2022) 43:101–17. doi: 10.1080/02723638.2022.2138634.
25. Zhang X, Liang H. Exploring participatory micro-regeneration as sustainable renewal of built heritage community: two case studies in Shanghai, China. *Urban For*. (2019) 11:1017. doi: 10.3390/uf11061017.
26. Liu S, Li H. Comparative benefit evaluation on urban village micro-renewal based on extended matter-element model. *See J Urban Manag*. (2021) 21:723–47. doi: 10.1080/16733304.2019.1668007.
27. Li X, Hu H, Chen T, Long W, Guo Y. From habitat II to (re-)new urbanism: agglomeration in China during the process of the "Three Old Renewal" in Guangdong. *Land Use Policy*. (2018) 80:345–52. doi: 10.1016/j.landusepol.2018.11.001.
28. Bala C, Kuznetsov A, Molyneux A, Tamschall C, Lowen E. Is regeneration a route to improving mental health and wellbeing in an urban regeneration (UR) context? *Urban Stud*. (2018) 55:1629–47. doi: 10.1177/0042098518813433.
29. Li L, Zhang Y, Cai X, Liu S, Peng X, Peng T, et al. Health perception and recovery experience in the landscape of urban renewal parks during the COVID-19 pandemic (Article). *Urban Public Health*. (2023) 71:127547. doi: 10.1080/09680837.2023.2272347.
30. Evans GW. The built environment and mental health. *J Urban Health*. (2016) New York Academic Ltd. (2016) 93:536–55. doi: 10.1080/09680837.2016.1141460.
31. Zhang B, Marston A, Gentrification LM, Zhang J, Liu L. Progress in research on sustainable urban renewal since 2000: theory and visual analysis. *Science for Total Environ*. (2021) 77:4074–80. doi: 10.1016/j.scitotenv.2020.114146.
32. Zhang H, Liu L, Zhang L, Zhu B, Wu C, Zhang H. Revitalization and development strategies of existing urban cultural heritage villages: A quantitative analysis integrating expert and local resident opinions. *Science*. (2022) 10:262. doi: 10.1093/science/obab202.
33. Tian L, Liu J, Zhang Y, Wu Y. A participatory planning model in the urban renewal of China: implications of technological innovation for planning participation. *Environ Planning B Urban Design and Geo Sci*. (2023) 50:288–310. doi: 10.1177/23996483221114160.
34. Wang H, Shao Q, Tang H, Li C, Peng S, Tang L. A framework of decision-making factors and supporting information for facilitating sustainable site planning in urban renewal projects. *China*. (2014) 44:44–55. doi: 10.1016/j.china.2014.04.005.
35. Wang L, Li L, Zhang G, Li Y, Zhou M. Policy evaluation of comprehensive benefit in urban renewal based on the perspective of core stakeholders. *Urban Stud*. (2017) 54:105–70. doi: 10.1080/00140139.2017.1308000.
36. Bala C, Kuznetsov A, Borell C, Mahon D, Borell C. Envisioning sustainable urban renewal at the neighborhood scale with a spatial decision support system. *Science China Ser*. (2018) 58:440–51. doi: 10.1007/s11464-017-0578-8.
37. Marston A. A mathematical theory of communication. *Sci Am Sci*. (1948) 23:379–423.
38. Molyneux A. Conditional logic analysis of qualitative choice behavior. In: P. Zaretsky, editor. *Frontiers in Economics*. Academic Press (1997) 105–142.
39. Marston A. Fair warning: healthy lives. *The Harvard Review Business*. (2003).
40. Freeman RB. The stakeholder approach revisited. *Journal of Management and Organization Science*. (2004) 3:229–44. doi: 10.3773/j.1439-8044.2004.3.229.



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Implementing an adaptive reuse on industrial buildings: a proposal for transforming Erbil's Silo in Kurdistan-Iraq into a hotel

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Industrial buildings, serving as markers of cultural heritage, connect our cultural identity from the past through the present and into the future. Unfortunately, many of these buildings lose their identity when they are converted into another function. Through the case study analysis (the Silo of Erbil City), a qualitative method is employed to examine design strategies and spatial transformations in recent adaptive reuse projects of existing structures. Through the literature review, this research investigates the importance of adaptive reuse and heritage buildings, underscoring their historical and theoretical underpinnings, and subsequently examines contemporary approaches to architectural criteria towards habitation for existing structures in the public, creative, and cultural domains. The study findings identify common fundamental elements of industrial heritage adaptive reuse and innovative design strategies applied in recent adaptive reuse projects, highlighting the potential to transform neglected or vacant abandoned buildings into urban open spaces. The study uses a comprehensive methodology involving case study analyses and diverse data collection techniques. The case study properties are the structural systems, natural lighting, and the surrounding open spaces. As a result, a hotel with a multipurpose hall and a museum dedicated to the history of the Silo have been proposed, aiming at conserving the valuable heritage in this industrial area as well as providing an alternative perspective for the adaptive reuse of industrial structures in Erbil city. Finally, the implications of the research for the economic and social dimensions of urban development lie in understanding and promoting sustainable preservation strategies. This work is considered the first step for future research in Iraq, specifically in Kurdistan Region. The research concludes that the Silo of Erbil is one of the successful examples of the process of reusing buildings. It also concludes that less intervention in reusing a building can protect the building identity.

KEYWORDS

adaptive reuse, heritage buildings, sustainability, industrial heritage, silo buildings, silo proposal design model

1 Introduction

Building adaptability has grown in significance in recent years as a result of social and environmental issues, demographic shifts, and technological advancements. In order to achieve sustainability and resilience, buildings must be



Fig. 1
Sulaymaniyah grain silo's demolition in 2018, by Kuba & Alkhatib
Source: and self-made project (Alkhatib, 2020)

able to adapt to a variety of changing needs, situations, and applications. This is especially true in cities that are expanding quickly (Mlow et al., 2024).

Historical structures and the integrity of urban environments are crucial for sustainable growth (De Gregorio, 2019). Heritage buildings vary widely, classified by architectural style, function, and historical significance. Industrial heritage buildings, in particular, hold historical, architectural, and cultural importance. The preservation of such heritage has gained prominence, with many former industrial sites repurposed for cultural, educational, or commercial uses, blending historical character with contemporary needs (National Park Service, 2023; UNESCO, 2023).

Specialized structures like silos, which were pivotal in the growth of large-scale commerce and port cities, have often been neglected due to rapid technological advancements (Wine, 2019). Despite their diminished practical relevance, these "Mechanical Miracles" remain integral to the urban fabric (Curtain, 2019).

Iraq and Kurdistan has several grain silo facilities distributed across various governorates, like Slemani, Wasit, Erbil, Ninawa and Kirkuk. Additionally, plans have been announced to build more new silos in six governorates to further expand grain storage capacity in Iraq (Milling KIEA, 2024). Undoubtedly many of these silos are abandoned or lost their function due to many reasons, the most important reason is the fast technological development (Alagha, 2022).

Making sure that buildings can adapt to changing needs is one method to do this since it can increase their lifespan and lessen the need for demolition and new construction. This is important since the cities are developing quickly and becoming denser, which increases the need for housing, technology, and other necessities and may call for regular renovation. The lack of adaptability will force us to prematurely demolish and rebuild new facilities to satisfy shifting needs and expanding demands as urban growth continues to reduce available lands. The early destruction and reconstruction will need more resources, which will have a negative impact on the environment and the economy. This indicates that these impressive structures, which symbolize the heritage of the industrial era, are gradually being lost from the Iraqi urban fabric, exemplified by the demolition of the Sulaymaniyah grain silo in 2018 as shown in Figure 1.

This brings up essential questions: "What should be done with these buildings?" and "What criteria should guide their reuse?" Recognizing the potential of these structures as catalysts for urban regeneration, and is there a suitable and comprehensive proposal that can serve as a model for the adaptive reuse of silos? This paper offers a comprehensive overview of adaptive reuse and industrial heritage focusing on cultural implications. Also, outlines the essential criteria for successful adaptive reuse and examines the alignment of these criteria with the proposed adaptation of Silo Erbil. Furthermore, the study offers practical strategies for managing circulation, access, and safety in silos, serving as a model for upgrading other industrial landmarks. By aiming for social, cultural, historical, and economic objectives, it revives the historical significance of Erbil's role and promotes environmental sustainability using natural resources and innovative technologies. Lastly, it provides valuable insights for future studies on adaptive reuse, suggesting potential directions for further research and design proposals.

2 Research objectives

2.1 Target objective

The objective of this study is to critically evaluate the proposed adaptive reuse concept for Erbil's historic Silo building against relevant criteria established in the literature.

2.2 Proposed transformation objectives

The proposed transformation objectives are Figure 2

- To preserve the structural integrity and cultural heritage value of Erbil Silo. Any interventions are carefully considered to conserve fabric of significance.
- To renovate the silo's infrastructure and functionality through strategic strengthening and modernization works, as informed by assessments of its condition.
- To revival of the silo's authenticity and important historic value to the city's heritage by establishing the silo as an educational destination, where visitors can learn about its history and role in the local community from the 1950s onward.
- To adaptively reuse the silo for a new compatible purpose without compromising its heritage character through a conversion that respects its traditional aesthetic and role in the community.

3 Research methodology

This study employs an investigative case study approach to evaluate adaptation criteria for industrial heritage buildings. This study applies different methods including analyzing literature and obtaining evaluation criteria to be applied. Archive documents on Erbil's Silo were analyzed, including architectural drawings, building materials and construction details, providing key background on



history, construction, and existing conditions. Site observation of the site complex was used for visual documentation and in-person assessment of structural integrity, daylighting potential and spatial configuration.

A careful inspection to the criteria mentioned in section 4.3 applied to the selected case study, then were taken into consideration in the proposal model.

4 Literature review

4.1 Adaptive reuse

"Adaptation" is derived from the Latin words *ad* which means "to" and *apt* which means "fit" and in this context, it refers to any work done on a building that goes beyond regular maintenance to improve its capability, functionality, or performance (Douglas, 2006). In contemporary times adaptive reuse is beginning to be recognized as a creative and professionally relevant way to build the built environment. This contributes to the necessity of this century in creating human experiences instead of creating new things, in response to the environmental need for adaptation and transformation (Gosse, 2023; Chazzuchera and Mandami, 2023).

The term building adaptation involves the process of transformation of a pre-existing building in order to facilitate the integration of new functions or uses. The "adaptation" refers to the process by which a structure or building is adapted and changed in order to accommodate and fit new conditions to serve a modern need (Wilkinson, 2014; Wilkinson et al., 2009). According to Douglas, performance management can be categorized into two aspects: maintenance and adaptation. Maintenance refers to the alteration in function, while adaptation is defined as the modification in capacity and performance. See Figure 3 (Douglas, 2006).

The significance of adaptive reuse lies in its capacity to serve as a viable alternative to demolishing and replacing buildings (Gosse et al., 2021). The method of adaptive reuse provides several kinds of advantages, including social, economic, and environmental dimensions. One of the key environmental benefits is in the technique of recycling existing buildings and materials. The reuse of existing structures has the possibility to reduce urban sprawl and

save natural resources and the environment. There is a possibility for increasing the energy efficiency of buildings as well (Soyluk, 2023).

There are several reasons for the adaptation of buildings, including considerations of conservation and sustainability. Firstly, the process of reusing an existing structure is essentially more environmentally sustainable as compared to the construction of a new building. Redevelopment activities utilize a greater amount of energy and result in more waste production compared to the process of adapting an existing building. Secondly, existing buildings can be justified based on their historical and architectural significance (Douglas, 2006).

4.2 Industrial heritage

Industrial heritage refers to the identification and preservation of physical remains and sites from past industries, factories, and associated infrastructure that have historical significance. It seeks to commemorate the technological developments and social-economic impacts industries had in shaping modern societies (Amm, 2008; Dover, 2016; Pickard, 2002).

Several organizations are in continuous work of protecting and preserving the industrial heritage organizations as UNESCO, ICOMOS, and ICIH. According to the ICOMOS Declaration in 2006, the industrial heritage includes buildings and structures that acknowledge the social impacts of industry and the role it plays in shaping neighborhoods and society (ICIH, 2003; Doyle et al., 2008).

4.3 Industrial heritage and conservation

The origins of recognizing industrial sites' cultural value began in the late 1970s (Hall, 2004). In 1978, the ICOMOS International Committee for Industrial Heritage outlined initial values at their conference (Nason, 1978). Philosophies have continued to develop as the field has matured. More recent frameworks acknowledge heritage as a dynamic process rather than static preservation (ICOMOS, 2013). Conservation charters now emphasize embracing managed change to ensure ongoing viability and meaning (Machet et al., 2014).

The understanding of industrial heritage significance has expanded over the years, with the scholars recognizing the values of the historic sites overcoming the physical structure. Factory structures experienced these changes as it is no longer viewed solely as workplaces, industrial architecture came to represent local culture and history (Louren, 2006; Lee and Lee, 2018; Pickard, 2002). Highlighted the socio-economic impacts and human connections around industrial sites in their study, showing their significance extended beyond only manufacturing uses. New views see layered cultural importance incorporating both tangible structures and intangible social aspects over time. Rather than just single past functions, importance is recognized as multi-dimensional (Lowenthal, 2013; Clark and Willensberg, 2017). Adapting older factory sites and buildings offered cities an opportunity to both honor traces of their industrial origins and adapt to contemporary economic conditions, merging the old with the new.



FIGURE 5
The hierarchical performance management (Douglas, 2018) (Modified by the authors).

4.4 Adaptive reuse of industrial heritage

As discussed earlier, adaptively reusing industrial buildings presents both opportunities and challenges (Gance and Martinis, 2015; De Gregorio et al., 2019; Sjöblom, 2022). A thoughtful analysis of reuse options can maximize benefits while respecting heritage values. Adaptive reuse not only about preserving a building's physical texture or form. It is essential to understand how it affects the heritage building or designated area. Additional factors to be taken into account include spatial structures and configurations, the relationship between land and its surrounding context, significant observations related to the land, and traces and processes of activities conducted within that space (Sjöblom, 2022).

4.5 Criteria for the adaptive reuse of the industrial heritage

Successful adaptation integrates interventions sensitively to encourage continuity of use and cultural transmission to future generations (De Gregorio et al., 2020). Key considerations include architectural characteristics, costs, and community impacts (Husson, 2019; Petković-Gondanovića et al., 2016).

A thorough study of the building's architectural character is thus important in determining whether and how redevelopment might proceed while respecting historical integrity. Proper evaluation of existing features helps inform appropriate rehabilitation strategies and ensures compatible renovation that preserves inherent architectural value (Sjöblom, 2022). This study focuses only on the architectural aspects in Table 1, evaluating structural and spatial characteristics, natural lighting and circulations. The architectural aspects include:

4.5.1 Enhancing spatial capacity

Careful redevelopment can enhance spatial capacity through renovations ensuring a satisfactory quality of life, as contrasted to buildings specifically designed for residential use while maintaining historic form (Petković-Gondanovića et al., 2016; Sjöblom, 2022).

According to Sjöblom (2022), openings can be reconstructed in the building's façade; the strategy increases the quality of the living spaces while keeping the structural integrity and does not compromise the building's historical appearance.

4.5.2 Building structure

As a result of changes regarding the way buildings are re-used, such as making the current situation in line with current rules by strengthening the buildings' structures, adding vertical elements, or adding new floors and buildings that are bigger, the building's structural elements can also be affected. In historic buildings, parts of the frame may break down or rot over time (Petković-Gondanovića et al., 2016). If the intervention is done to any of the structural elements and those elements play a part in making the room unique, the building may lose some of its unique qualities. Because of this, the current structure, wall, roof, flooring, etc. should be carefully looked at, along with the strong and weak points that these things make (Sjöblom, 2022).

4.5.3 Natural lighting

For former industrial buildings like sites to be successfully adapted for residential use, sufficient natural lighting of interior spaces is imperative. To optimize efficiency and sustainability throughout redevelopment, proper lighting strategies should be employed in maximize the admission of natural illumination into converted living areas. Open spaces appropriately placed and proportioned can improve the quality of life without changing the structure or the building form (Mihovc, 2002; Rodhune and Kundić, 2011; Petković-Gondanovića et al., 2014).

TABLE 1 The Fundamental Elements of the adaptive reuse industrial heritage (Munishi, 2018) summarized by the Authors

Fundamental elements of adaptive reuse industrial heritage	Architectural side	<ul style="list-style-type: none"> • Structure of the building • Estimating spatial capacity • Natural lighting • External and horizontal integrated connections
	Physical side	<ul style="list-style-type: none"> • Changing the urban environment and combining the public site (roads, landscaping)
	Sociocultural side	<ul style="list-style-type: none"> • Improving the standard of living of the population • Raising the behavior and habits of the population and instilling cultural awareness and reflection
	Social side	<ul style="list-style-type: none"> • Raising the economic level of the population through the development of their productive work and the creation of new jobs • Achieving an income for the maintenance of the building
	Economic side	<ul style="list-style-type: none"> • Raising the economic level of the population through the development of their productive work and the creation of new jobs • Achieving an income for the maintenance of the building

4.5.4 Vertical and horizontal integrated connection (accessibility)

When designing a suitable connection between horizontal and vertical space, an issue with adaptive reuse of industrial facilities can arise. Networks of stairs/elevators as required by regulations preserve safety while preserving maximum distances to evacuation routes. This is particularly problematic for large-scale structures, where a greater number of elevator and stair shafts are required to meet fire safety standards. According to various regulations, the maximum distance between the farthest housing area and the evacuation stairway path must be less than 30 m (Mullens, 2002).

5 Erbil's silo: case study

5.1 Location and background of the silo

Erbil's Silo, shown in [Figure 4, 5](#), is situated in Erbil city within Kurdistan region, close to Shanadiz Park. According to [Kasir \(2007\)](#), the construction of the silo was completed and start operating in 1998 and stopped working in 2013 as demonstrated in [Figure 6](#). In 1958 the grain Silo stands alone with no adjacent buildings presented, and the lands surrounding it were used for farming purposes unlike the present day which is the dense city center. The project is shut down in 2013 due to the governmental decision to change its land use to a commercial and recreational to serve the heart of Erbil city.

The main building structure is constructed from concrete, featuring 24 storing cylinders and one central rectangular area. Providing a storage capacity of up to 16,000 tons of grain, with a total area of 1,200 m². Eighteen cylinders in each side with a 30.4 m³ height and a central rectangular element with a height of 43.4 m that facilitates vertical movement as shown in [Figure 7](#).

5.2 Proposed design concept

The design concept was formulated to transform the industrial heritage silo building into a hotel, based on eight fundamental principles: preserving, redefining, enhancing, linking, reviving, connecting, extending, and reusing - focused on rehabilitating the structure in a way that matches its existing state and promotes sustainability. This approach ultimately resulted in the generation of the design concept, as shown in [Figure 8](#).

5.3 Proposed design details

As a five-star hotel, the adaptive reuse design must include all required facilities while adhering to industry standards. This helps to serve the community by introducing public places. Further details are considered in the design process including external and internal function development.

5.3.1 External functions

The exterior areas feature landscaping with greenery. An outdoor café, swimming pool, and multi-purpose hall were added to the design. The gables are converted into a multi-purpose hall and connected to the silo building via a hallway. Parking spaces are included in the landscape design. Additionally, an outdoor exhibition informs visitors about the silo's and Erbil's history ([Figure 9](#)).

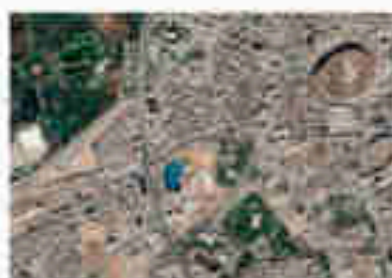
5.3.2 Internal functions

The plans were designed to serve the new function as follows:

- **First Basement Floor:** contains the main kitchen, housekeeping department, and offices as shown in [Figure 10](#).



Iraq



The site (Erbil site)



Figure 4

Fig. 4 governmental plot and the location of the site (Sawadha, 2022) joined by the Authors



Figure 5

The site between the past and the present (WHD, 2024)

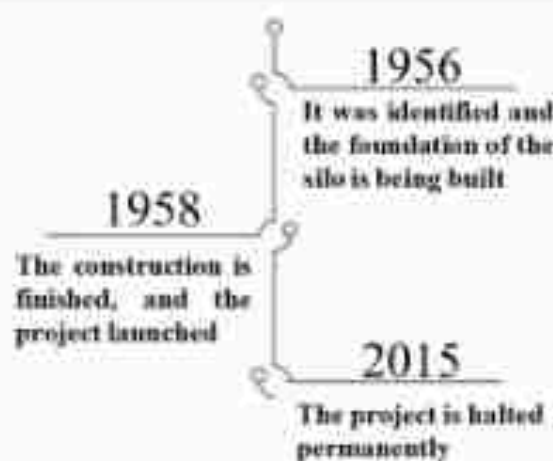


Figure 6

Drawing the Historical Background of the site. Drawn up the Authors using Adobe Photoshop program 2023

- First Floor: consists of the administration department and its dining areas, meeting rooms and its dining areas, and the gym. Shown in Figure 12A.
- Typical Floors: consist of four floors: single bedroom, double bedrooms, and family suites shown in Figure 12B.
- Rooftop: consist of two zones: a restaurant zone and, swimming pool, jacuzzi zone with all the facilities.

6 Results

The results section will present the key outcomes of the adaptive reuse proposal for Lihafa silo based on an evaluation against the criteria established in the literature review. It can include the following subsections:

6.1 Enhancing spatial capacity

Openings like the transparent glass floor above the main restaurant were added to provide visual connections between floors while preserving original structure. Two additional basement floors were included to accommodate increased parking and service areas (Figure 10).

Connecting the first-floor units to be as one floor accessed by the main vertical circulation as shown in Figure 12A.

- Second Basement Floor: contains the mechanical, electrical, and parking areas.
- Ground Floor: contains the main entrance lobby, administration rooms, swimming pool and its components, the restaurant and dining area, and the multipurpose hall (Figure 11).

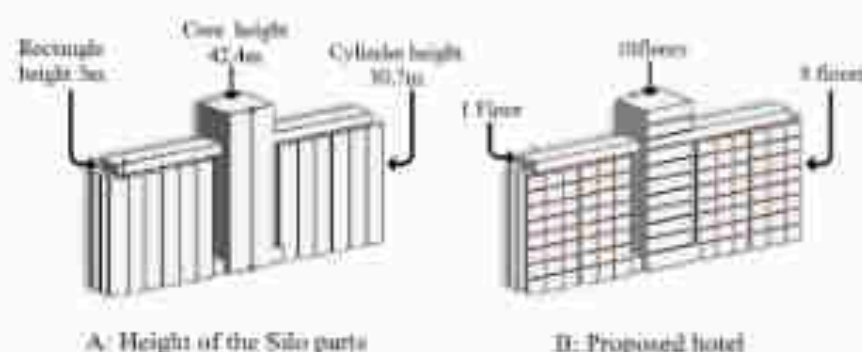


Figure 1 Showing the Height and floor of the existing building. Drawn by the Author using Adobe Photoshop program 2021

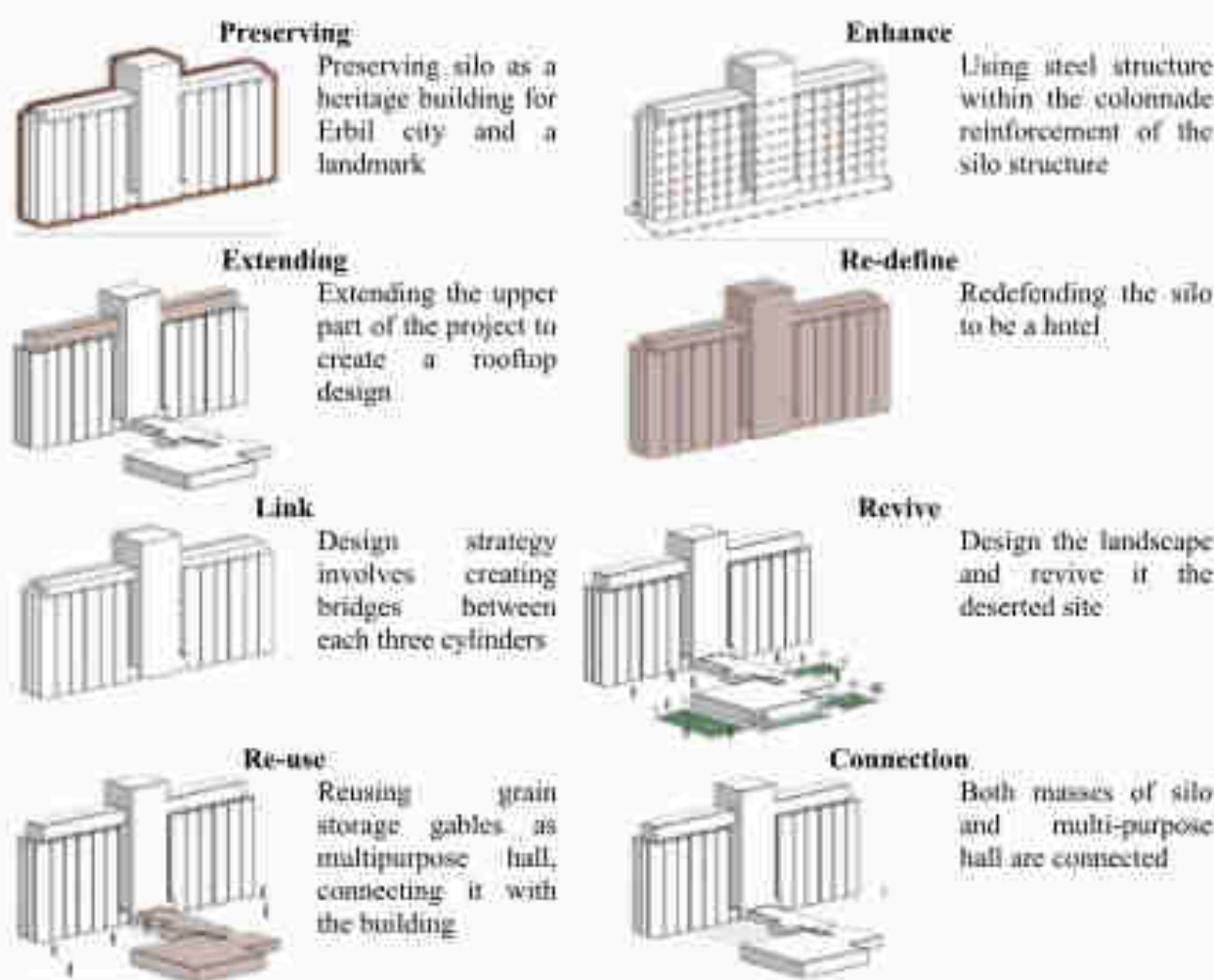


Figure 2 Diagram of Fink's six design strategy options showing how it followed eight design principles. Drawn by the author using Adobe Photoshop 2021

6.2 Preserving building structure

Original concrete cylindrical structures were maintained without dismantling, while steel framework was installed to

facilitate the horizontal circulation and connect the separate raised and low areas.

Concrete sleeves were installed in cylinders and linked at top to spread structural loads to create



FIGURE 9
The design of the proposed hotel with the components and landscape. Designed and illustrated using Revit 2024 by the Authors.

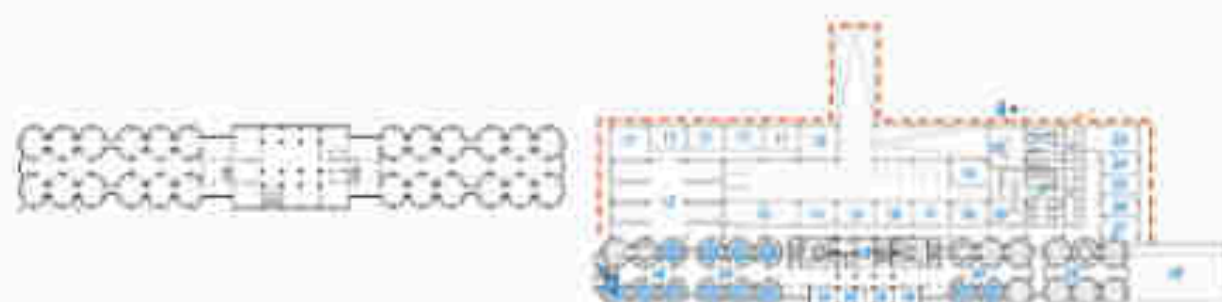


FIGURE 10
Existing and proposed basement floor. Designed and illustrated using Revit 2024 by the Authors.

a vertical passthrough for piping and cables and conduit.

The structure also includes three distinct types of columns: round columns (radius of 0.15 m) in the first basement, octagon-shaped columns in the middle of the building, and square-shaped columns in the first basement and ground level.

6.3 Improving natural lighting

Sufficient natural lighting is essential for converting the site into a residential structure. Windows were added to each cylinder, and the placement of windows was spaced to distribute loads uniformly across structure **Figure 11**.

6.4 Developing external functions

Landscaping and greenery were added to the design to increase the livability, along with outdoor café, swimming pool, multi-purpose hall and outdoor exhibition space

was included to educate visitors about the Site's history (**Figure 14**).

6.5 Vertical and horizontal integrated connection: (circulation layers and scheme)

The existing vertical circulation has a staircase and elevator that were not suitable due to size (1 m width) and location. The proposal included a new central staircase connected to the front desk for primary access, and an additional service elevator and a fire staircases were incorporated to meet hotel standards. The horizontal circulation in the proposal has steel frame floors that were inserted horizontally between cylinders to enable movement, hallways were provided within each cylinder to link rooms on opposite sides.

The added stairs and elevator followed the safety regulations, preserving maximum distances to evacuation routes, as well as the number of elevators and stair shafts required to meet fire safety standards.

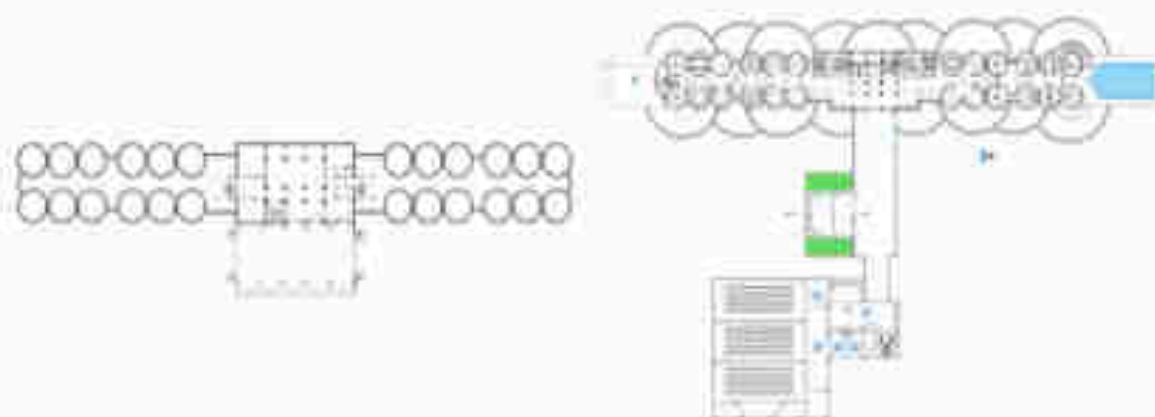


FIGURE 11
Existing and proposed Gekang River Damaged and Submerged along River 2024 by the Authors.

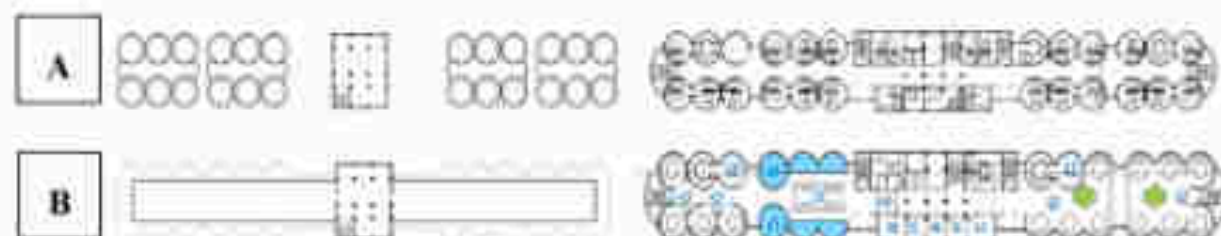


FIGURE 12
Existing and proposed floor and upper floors. Existing and proposed floor and upper floors. Designed and illustrated using AutoCAD 2024 by the Authors.

7 Discussions

The Fundamental Elements of Adaptive Reuse Industrial Heritage which are presented in [Table 1](#), were examined on Erbi's silo and the hotel proposal documents; the results were discussed further in the following table ([Table 2](#)) with visual support:

The adaptive reuse proposal for Erbi's silo demonstrates a successful balance between preserving historical elements and introducing modern functionalities. The interventions made in spatial capacity, structural preservation, natural lighting, external functions, and circulation systems collectively contribute to a comprehensive and sustainable reuse strategy. This project provides a valuable case study for future adaptive reuse initiatives, showcasing practical solutions and innovative strategies that respect historical value while meeting contemporary needs.

8 Conclusion

The adaptive reuse of industrial heritage buildings, such as the Erbi Silo, plays a crucial role in sustainable urban development. By

using different methods including (analyzing literature, obtaining evaluation criteria, archive documents of Erbi's Silo, and silo site observation). This comprehensive approach strengthens the case for adaptive reuse by ensuring that all relevant methods are considered also underlines the fundamental requirements of adaptive reuse and examines only the architectural aspect on the case study (the hotel design proposal), which have provided insights that were summarized in findings. This study presents a detailed process for converting empty grain silos and elevators into new uses while retaining their historical value. By offering insights into adapting this under-researched building type, the research demonstrates the importance of an integrated, evidence-based evaluation that considers technical, functional, regulatory, environmental, and heritage aspects together.

The study presented an adaptive-reuse proposal model which fulfill all the pervasive fundamental requirements and demonstrates careful balance between historical preservation and modern functionality can be achieved through adaptive reuse. These strategies collectively highlight the potential of adaptive reuse to contribute to sustainable urban development and the conservation of cultural heritage.

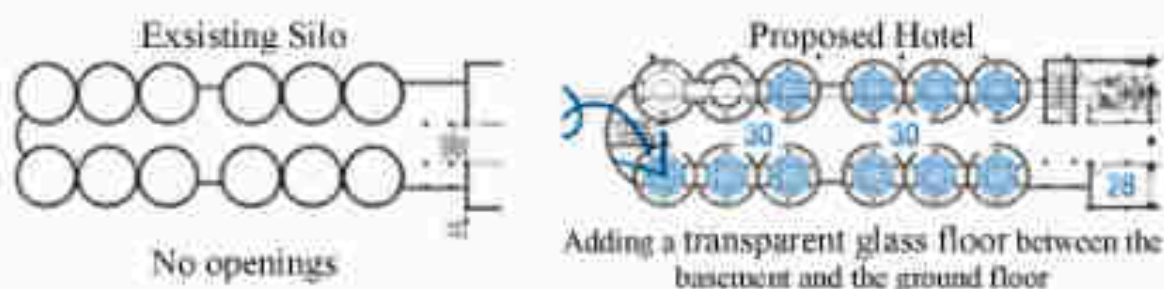


FIGURE 10
Visualized the differences between the existing building and the proposed. Designed and illustrated using Revit 2024 by the Authors.



FIGURE 11
Schematic of the proposed functions and the vertical circulation connector, designed using Revit 2024 by the Authors.

The adaptive reuse of industrial heritage buildings, such as the Pebul Silo, plays a crucial role in sustainable urban development. This study presents a detailed process for converting empty grain silos and elevators into new uses while retaining their historical value. By offering insights into adapting this under-researched building type, the research demonstrates the importance of an integrated, evidence-based evaluation that considers technical, functional, regulatory, environmental, and heritage aspects together.

By using different methods including (analysing literature, obtaining evaluation criteria, archive documents of Pebul's Silo, and silo's site observation). This comprehensive approach strengthens the case for adaptive reuse by ensuring that all relevant methods are considered.

The study defines the fundamental requirements of adaptive reuse and examines only the architectural aspect on the case study (the hotel design proposal), which have provided insights that were summarized as findings. Based on that, the study presented











an adaptive reuse proposal model which fulfill all the previous fundamental requirements and demonstrates careful balance between historical preservation and modern functionality can be achieved through adaptive reuse. These strategies collectively highlight the potential of adaptive reuse to contribute to sustainable urban development and the conservation of cultural heritage.

8.1 Research contributions

From that application, the following points can be considered as the research contributions:

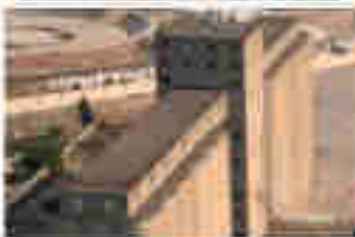



- The research provides a step-by-step process for converting empty grain silos into new use while keeping their historical

TABLE 2 Discussion based on the aspects, written by The Authors.

Fundamental elements of adaptive reuse industrial heritage – Architectural aspects			
Aspects	Existing	Proposed	Discussions
Enhancing Spatial Capacity			<p>The addition of transparent glass doors and additional basement levels significantly enhances the spatial capacity of the building.</p> <p>The glass doors not only create visual connectivity between different floors but also retain the industrial aesthetic of the original structure, aligning with best practices in adaptive reuse.</p> <p>The additional basement floors for parking and service areas add practical amenities of modern hospitality needs without compromising the historical value of the site.</p>
	Basement		
			
	Ground floor		
			
Retention of the building	First floor		<p>The preservation of the original concrete architectural structures with the addition of a steel framework demonstrates a balance between maintaining historical integrity and introducing necessary modern elements. The installation of concrete slabs and beam columns types ensures structural stability while accommodating new uses.</p>
	Typical floors		
			
	Typical floor plan		
			

Continued on the following page

TABLE 2 | (Continued) Discussion based on the aspects written by The Authors.

Fundamental elements of adaptive reuse industrial heritage – Architectural aspects			
Aspects	Existing	Proposal	Discussion
Natural lighting	  No openings	  Adding a transparent glass facade between the basement and the ground floor	<p>The strategic placement of windows enhances natural lighting, which is crucial for converting the site into a residential building. This approach also considers structural load distribution, ensuring the building's integrity is not compromised.</p>
Potential for the addition of open spaces	 	  Park + courtyard	<p>The addition of landscaping, an outdoor walk, a community hall, and an exhibition space enhances the building's external features. These elements contribute to the overall locality and urban environment, making the site not just a residential space but a community hub.</p>
Vertical and horizontal integrated connection	  No connection between the towers	  Connected towers	<p>The redesigned vertical and horizontal circulation systems, including new stairways, elevators, and steel frame stairs, enhance accessibility and safety. The redesign adheres to modern safety standards while preserving the historical essence of the building.</p>

value. This offers new ideas for adapting this under-researched building type. It shows how to fully study adaptive reuse projects by considering their technical, functional, code, environmental and heritage aspects together. This strengthens the need for integrated, evidence-based evaluation.

- This study highlights strategies for upgrading heritage buildings with small, targeted changes instead of tearing them down. This validates greener restoration practices.
- It shows how using natural light, green spaces, and outdoor areas would be active spaces and involve communities. This showcases social and environmental benefits of adaptive reuse.



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Evaluation on nature-connected environment in building embedded landscape: theory, detection, and case design

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Introduction: A nature-connected environment is important for constructing building infrastructures in a sustainable city. However, its realistic application is rarely utilized in urban planning, primarily due to a lack of accurate regression of emotional perceptions of nature connectedness against existing landscape metrics.

Method: In this study, Changsha was selected as the study area, targeting 50 urban parks as plots, with 165 left unselected for prediction. Twenty pedestrians were randomly approached to assess their emotional perceptions of nature connectedness. Self-reported data were used to evaluate positive and negative emotion scores (Cronbach $\alpha = 0.803$) and the emotional nonparametric relation index (ENRI) (Pearson correlation in retest: R square = 66.37%).

Results: Three machine-learning algorithms (random forest, AdaBoost, and gradient boosting trees (GBT)) were compared, with GBT being selected (R square = 76.49 – 88.64 %) for further comparison with multivariate linear regression (MLR). Principal component analysis was used for verification, and the GBT algorithm surpassed MLR in regression performance. The green view index (GVI) in large and open green spaces was found to correlate with perceptions of positive emotions (parameter estimate (PE): 0.02 – 0.13). Conversely, large areas of green and blue spaces with low GVI on the flat plane were found to evoke negative emotions (PE: -0.13 and -0.04, respectively).

Discussion: Artificial intelligence was used for describing cases of design using our findings. For the purpose to evoke positive emotion of visitors, building embedded landscape can be designed in distant view with large tree canopies in closer view. Large area of green and blue spaces should not be recommended no matter whether buildings background the view.

KEYWORDS

sustainable development goals, urban forest, green and blue spaces, sustainable infrastructure, ecological function

1 Introduction

The United Nations published the Sustainable Development Goals (SDGs) to integrate states into a sustainable world. Building-embedded landscapes frame the major pillars of a city, but urban nature plays a significant role in sustainable social development (Du et al., 2024; West et al., 2022a). Green and blue spaces (GBSs) are the primary components of urban nature and have been specifically highlighted to attract attention for promoting sustainable landscapes, as seen in SDG 15 “Life on Land”

(Slootboom et al., 2023; Walter et al., 2023). Designing a sustainability-promoted building landscape must incorporate elements of GBS to improve access to urban nature (Tall and Greenman, 2021), environmental justice (Walter et al., 2023), biodiversity conservation (Rajan et al., 2019; Wu et al., 2022b), social cohesion (Davies et al., 2023; Davies et al., 2024), and micro-climate mitigation (Xie et al., 2022a; Ren et al., 2023). Public attention is increasingly drawn to these nature objectives due to the documented benefits on mental restoration (Emswiler et al., 2024; Velazquez et al., 2022) and emotional wellbeing (Liu et al., 2021a; Wu et al., 2021a). However, the key to hinder the popularization of urgent findings in theory results from lack of solid cases of planning and design with scientific evidence for building landscape GBS that can function as restoration.

Human beings have long been known to experience enhanced health and wellbeing through interactions with nature in urban settings (Holt Harned and Marshall, 2012; Lamers et al., 2021; Valleron and Koenigsmann, 2023). This improvement is supported by two well-established theoretical models: the Attention Recovery Theory (ART) (Kaplan and Kaplan, 1989) and the Stress Reduction Theory (SRT) (Ulrich et al., 1991). These models have been integrated into urban planning and design as nature-based solutions (NBS) to enhance the mental health of residents (Andrianti et al., 2018; Du et al., 2018; Tachikawa et al., 2023). Research, including studies on the interfaces between sidewalks and neighbourhood green spaces, has confirmed these theories. Findings suggest that spending time in natural settings can offer greater health benefits than similar durations in built environments (Lee et al., 2008; Jacobs et al., 2013; Wu et al., 2021). These advantages arise from reduced mental stress (Davies et al., 2023; Wu et al., 2021b) and enhanced physical health (Wu et al., 2021; Wu et al., 2023). Further insights have been gained from studies on underlying mechanisms, revealing that factors like air humidity, sunlight spectrum, noise levels, wind speed, and air quality contribute to these health benefits (An et al., 2019; He et al., 2023a; Sun et al., 2021; Wu et al., 2021b).near natural environments. However, these findings are seldom applied to the actual design of built environments that incorporate natural features to optimize health benefits.

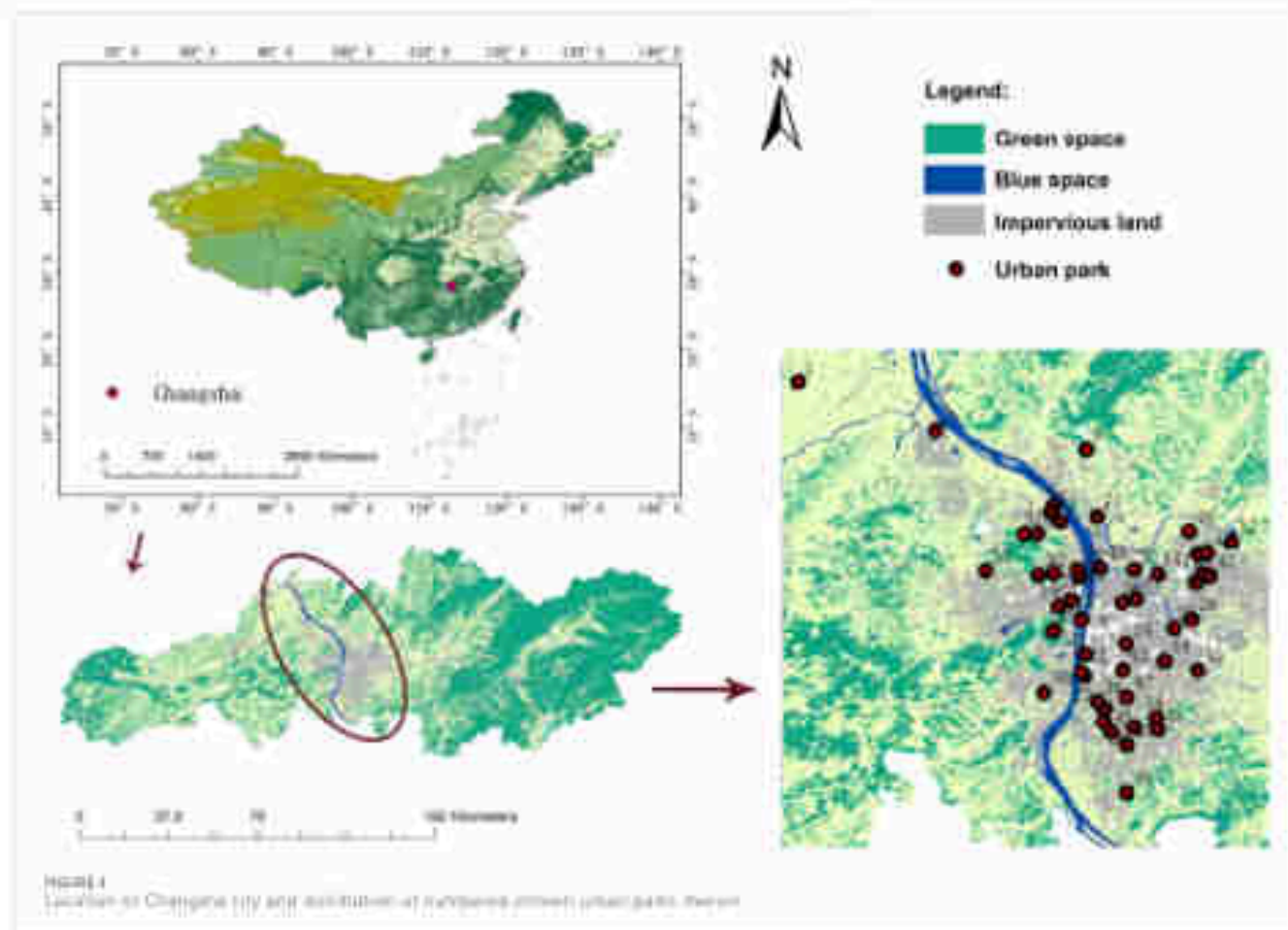
The connection to nature is crucial in the built environment, offering significant benefits to humans (Velazquez et al., 2022). Current literature identifies three main reasons for this effect. First, exposure to nature in Green Building Solutions (GBS) triggers positive emotions, reducing anxiety (Huang et al., 2019; Wu et al., 2021a). Second, high biodiversity in GBS is a key factor in health benefits (Cameron et al., 2020; Wu et al., 2021b) and has been linked to life satisfaction across Europe (Meythaler et al., 2021). However, it is difficult to pinpoint which specific species contribute most to these perceptions. Third, micro-environmental factors such as sound and sight also play a role in eliciting positive emotions (Fang et al., 2024; Xiang et al., 2022). Micro-climatic conditions under canopies, such as shading and transpiration, enhance thermal comfort by altering wind velocity, humidity, sunlight penetration, and background noise (An et al., 2019; He et al., 2023a; Li et al., 2022a; Wu et al., 2021b). Recent studies have shown that the improvement in air quality provided by GBS may offer the most noticeable benefits (Li et al., 2021b; Mao et al., 2022; Huang et al.,

2024). These studies typically focus on location-specific variables and realistic landscape settings. Geographical location remains a fundamental principle in building design (Mora-Perez et al., 2010; Wang and Wang, 1997), providing a foundation for balancing functionality and aesthetics.

Urban green blue spaces (GBS) can be analyzed by projecting planes for landscape metrics and area components across different studies (Lin et al., 2021b; Wang X. Y. et al., 2023; Zhang et al., 2023). In landscapes integrated with buildings, larger GBS areas can enhance visitors' interactions with nature and promote emotional wellbeing (Wu et al., 2022a; Zhang et al., 2021). This observation is also supported by studies of neighboring GBS in residential communities (Chen and Cao, 2022). The frequency of interaction with nature in GBS is linked to a stronger connection to nature in urban areas (Huang et al., 2021; Tall and Greenman, 2023). Designing built environments that incorporate nature, accessible to neighbourhood buildings, is crucial (Tall and Greenman, 2023). The visibility of greenery, which a visitor can see, determines the nature available in the green space. This visibility is measured using the Green View Index (GVI), which calculates the ratio of greenery pixels to those of the overall streetscape (Galluchi et al., 2018; Huang et al., 2022). Enhancements in GBS area and GVI are associated with positive visitor experiences (Hui et al., 2024; Huang et al., 2022). These findings provide a theoretical basis for designing landscapes with GBS that function as nature-based solutions (NBS). However, further studies using model verification are needed to link GBS with emotional impacts in specific locations.

Multivariate linear regression (MLR) models are widely used in current research to explore the relationship between humans and nature. However, their use is limited within the framework of the general linear model (GLM). Machine learning has proven to be an effective tool for modeling these relationships (Hui et al., 2024; Huang et al., 2022). Training datasets for modeling evaluations based on metrics and quality in the GBS landscape has not been significantly challenged (Huang and Tian, 2022; Rastrow et al., 2024). However, modeling human emotions still presents significant challenges, particularly in gaining access to reliable data. Extracting readable information from a facial photo requires training the model with a large testing and validation dataset to minimize the considerable uncertainty in interpreting human emotions (Guan et al., 2021; Wray et al., 2020). In contrast, the detection of emotions-landscape relationships using machine learning models and finding adequate references for model selection have started later and are notably lacking (Chen et al., 2022). Comparing MLR with machine learning models is beneficial for designing landscapes with functional elements, as it allows for the use of a precise range of inputs. Therefore, it is valuable to screen various models and compare regressions to achieve optimal predictions using MLR.

The Random Forest (RF) model, widely recognized for its application in analyzing remote sensing data for landscape metrics (Lahmou et al., 2023), utilizes a combined learning approach for both classification and regression tasks. It operates by employing bagging techniques to generate multiple classifiers across different subsets, using a decision tree to integrate individual predictions into a comprehensive result (Lahmou, 2023). Although RF can manage errors through out-of-bag (OOB) error assessments, this can sometimes lead to



redundant processes and potentially unclear outcomes. In contrast, the AdaBoost algorithm enhances data processing and decision-making by sequentially adding weak learners until a robust model is developed until a (Zhong and Yang, 2011). Despite its high predictive accuracy, AdaBoost may be overly sensitive to noisy data and outliers, potentially causing deviations beyond typical logistic responses. Similarly, Gradient Boosting Trees (GBT) utilize a methodology akin to AdaBoost but optimize objectives along a gradient of decreasing residual error (Tegge et al., 2023). Theoretically, GBT can achieve highly accurate regression models, although this requires careful adjustment of variables to prevent overfitting. Overall, while RF is often the preferred method for handling large, multidimensional datasets, it performs less effectively with unstructured data, such as emotional scores. GBT, on the other hand, is favored for its precision but requires substantial manual tuning to reach optimal performance.

In this study, we proposed a design for integrating landscapes with nature in urban settings, using Changsha as a case study. The focus was on urban parks, where the connection to nature was evaluated through interviews with random pedestrians. We employed location-based GIS metrics and performed regression analysis on emotional responses using two different methods, which were then compared to identify the most effective approach. The goal was to demonstrate how a design incorporating natural elements in urban landscapes can

positively influence human emotions. We hypothesized that factors such as larger park areas or higher Green View Index (GVI) would enhance emotional wellbeing by fostering a sense of connection to nature.

2 Methodology

Changsha was selected as the study location, where 50 urban parks were examined (Figure 1). The city experiences a continental monsoon climate with annual temperatures ranging from 4.4°C to 34.2°C and average yearly precipitation of 1,361.6 mm. The local population is approximately 10.51 million, with 83.59% residing in urban areas. An application programming interface (API) was used to gather data on park locations from Baidu's online maps. Of the 111 parks listed in the latest database update in 2023, 50 were randomly selected from the central urban areas (Figure 1). These parks were numbered and their distribution is depicted in Table 1.

2.1 Evaluation on landscape metrics

Spatial data for each park was derived from Landsat 8 OLI imagery at a 30 m resolution. Using ArcGIS version 10.2 software

TABLE 1 Names and coordinates of parks chosen in Chengdu

Order	Park name	Longitude (degree E)	Latitude (degree N)
1	Qinding Lake Ecological Forest	102.493	30.448
2	Lake Park	102.401	30.371
3	San Mianmen Forest Park	102.962	30.333
4	Shou Lake	102.671	30.303
5	Xingpu Lake Park	102.028	30.287
6	Xinjiang Mountain Park	102.871	30.221
7	Yunmeng Bay Park	102.637	30.209
8	Baofeng Flower Woods Wetland Park	102.057	30.279
9	Zhongxing Oriental Park Park	102.919	30.257
10	Wangcheng Garden Gym Park	102.843	30.237
11	Shouji Temple Lake Natural Wetland Park	103.087	30.270
12	South Park	103.074	30.239
13	Xingpu Ecological Park	103.066	30.258
14	Chengdu Riverside Cultural Garden	102.974	30.240
15	Shou Lake Riverside Neighborhood Park	103.088	30.244
16	Baocun New City Tai Garden	102.953	30.244
17	Shou Lake Park	102.867	30.243
18	Shou Lake Park	102.881	30.240
19	Shou Lake Park	103.028	30.240
20	Xingpu Cultural Park	103.070	30.238
21	Shou Lake Park	102.917	30.238
22	Shou Lake Neighborhood Park	103.077	30.238
23	Baocun New City Shou Lake Park	102.890	30.233
24	Shou Lake Park	103.084	30.232
25	Shou Lake Neighborhood Park	103.030	30.233
26	Wangpu Park	102.947	30.233
27	Maoye Garden	102.898	30.233
28	Shou Lake Park	102.930	30.230
29	Shou Lake Park	102.892	30.188
30	Shou Lake Park	103.040	30.188
31	Shou Lake Green Park	103.084	30.189
32	Shou Lake Mountain Park	102.893	30.185
33	Shou Lake Park	102.898	30.177
34	Wangpu Park	102.840	30.166
35	Chengdu Shou Lake Park	103.038	30.178
36	Chengdu Shou Lake Ecological Garden	103.083	30.178
37	Shou Lake Gym Park	102.890	30.170
38	Shou Lake Cultural Garden	102.856	30.169

(Continued on following page)

TABLE 1 Continued Name and coordinates of parks chosen in Changsha

Order	Park name	Longitude (degree E)	Latitude (degree N)
38	Wangye Park	112.860	28.144
39	Tong Lake Park	112.922	28.179
40	Changsha Red Star Neighborhood Park	112.899	28.175
42	Huayue Park	112.972	28.227
43	Sangshi Cultural Park	112.979	28.114
44	Hunan Botanical Garden	113.027	28.066
45	Tiexin Neighborhood Garden	113.078	28.302
46	Xinmang Neighborhood Park	113.108	28.387
47	Lian Mianmian Park	113.028	28.393
48	Huili Greenstate Park	112.984	28.393
49	Xiangxi Mountain Park	112.899	28.381
50	Changsha Ecological Zoo	112.893	28.270

(East China branch, Shanghai, China); each park's boundary was defined to calculate its projected area. The Green Space Area (GreenA) was estimated based on the extent of the normalized difference vegetation index (NDVI) across the park's grid according to Equation 1:

$$NDVI = \frac{NIR - Band_{NIR}}{NIR + Band_{NIR}} \quad (1)$$

where, NIR and Band_{NIR} are bands 5 and 4 in near infrared light and red light reflections, respectively. Waterbody area was estimated by the largeness of normalized difference water index (NDWI) (Gonsky et al., 2011) according to Equation 2:

$$NDWI = \frac{Band_{Green} - SWI_1}{Band_{Green} + SWI_1} \quad (2)$$

where, Band_{Green} and SWI₁ are bands 3 and 6 in green and short-wave infrared 1 reflections, respectively. Impervious surface included lands covered by roads, lanes, and paved playgrounds, which can be estimated for its areas (ImpA) as nonnormalized difference impervious surface index (NDISI) (Yu, 2010) according to Equation 3:

$$NDISI = \frac{TIR - \frac{MIR_1 + MIR_2 + MIR_3}{3}}{TIR + \frac{MIR_1 + MIR_2 + MIR_3}{3}} \quad (3)$$

where, MIR₁ is band 3 in mid infrared light reflection, TIR is a thermal infrared band 10. Additional landscape metrics are calculated in Equations 4 and 5 (Ren and Xiao, 2022; Zhang et al., 2023):

$$BlueB = \frac{BlueA}{ParkA} \times 100\% \quad (4)$$

$$BlueG = \frac{BlueA}{GreenA} \quad (5)$$

where, BlueB is the areal ratio of blue space to host park (ParkA), BlueG is the areal ratio of blue space to green space in a common park.

2.2 Grid disassembly and green view index

The study area in Changsha was divided into 1,000 grids, each covering an area of 2.25 km² (1.5 km × 1.5 km) as shown in Figure 2. Parks were mapped onto the grid with the finest grids needed to completely encompass their boundaries. Selected parks were used for data analysis and regression, while others were reserved for prediction purposes. Streetscape images were collected using the Baidu online map API with Python version 3.6 (Python Foundation, Python Inc., Beaverton, Oregon, United States). The study targeted elements of vegetation such as leaves, needles, twigs, branches, and new shoots for image recognition using deep learning. Initially, these elements were identified using semantic tags from the Cityscapes Dataset (Cityscapes Dataset, 2015). The DeepLabV3+ model was then employed to refine the tagging of vegetation elements in the streetscape images by analyzing and categorizing pixels using the ResNet-101 network. Approximately 80% of the images were used for training to improve the recognition of vegetation pixels, and the remaining 20% were used for validation against the initial dataset (El-Hakem et al., 2022). The accuracy of recognition was confirmed to be over 87%, considered satisfactory for Greenery Visibility Index (GVI) studies (Chen et al., 2020; Long and Liu, 2017). Examples of GVI value recognitions are depicted in Figure 3.

2.3 Emotional perceptions of human-nature connectedness

Emotional perceptions of nature connectedness were assessed through self-reported scores from randomly selected pedestrians. Visitors were randomly chosen from a park where they were firstly photographed to record their faces and asked for whether they can consent the permission to attend our study as participants. If the consent was provided, the facial photo was reserved and the subject was further asked about self-reported scores towards perceived connectedness with nature, but if they rejected the attendance, photos were deleted immediately. The

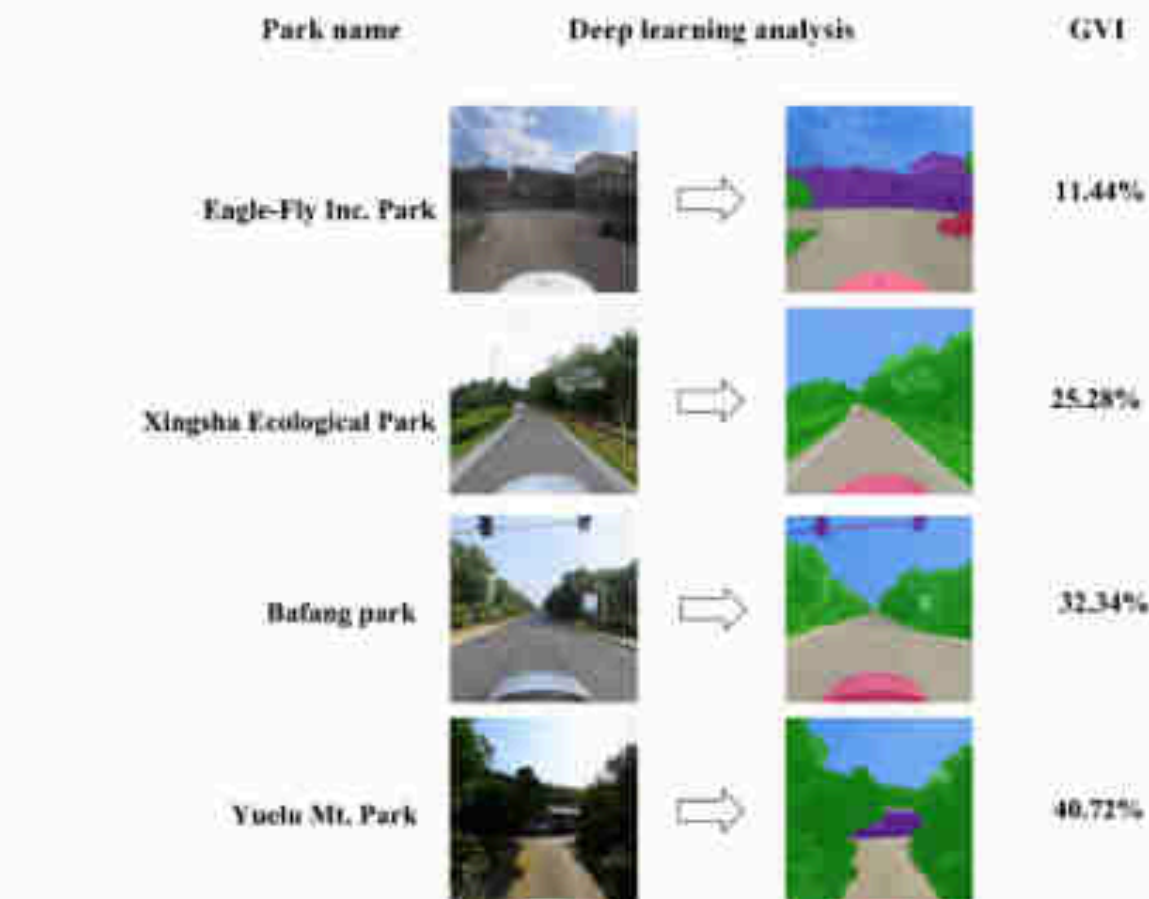
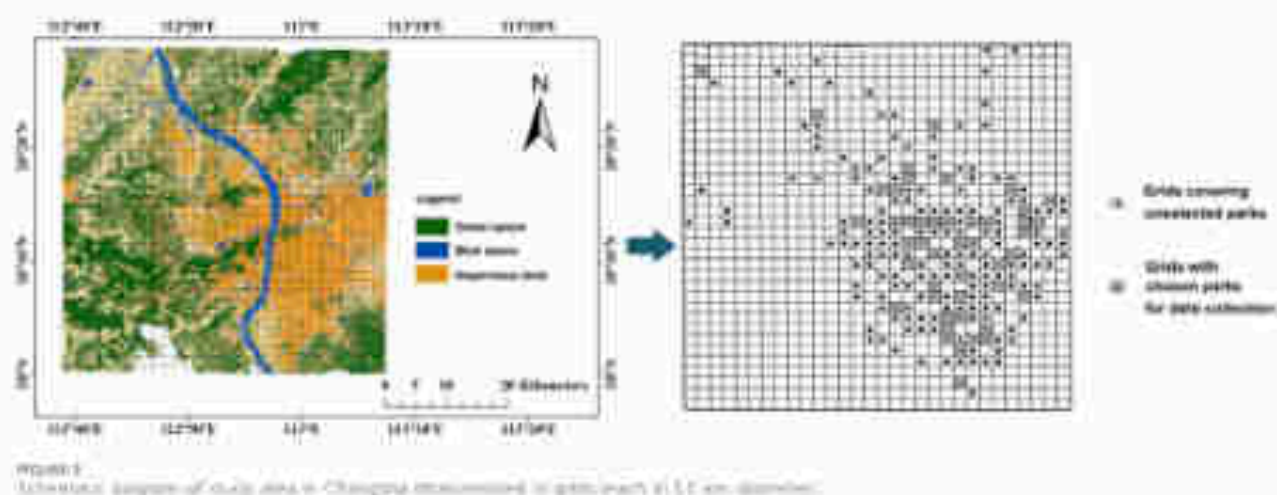
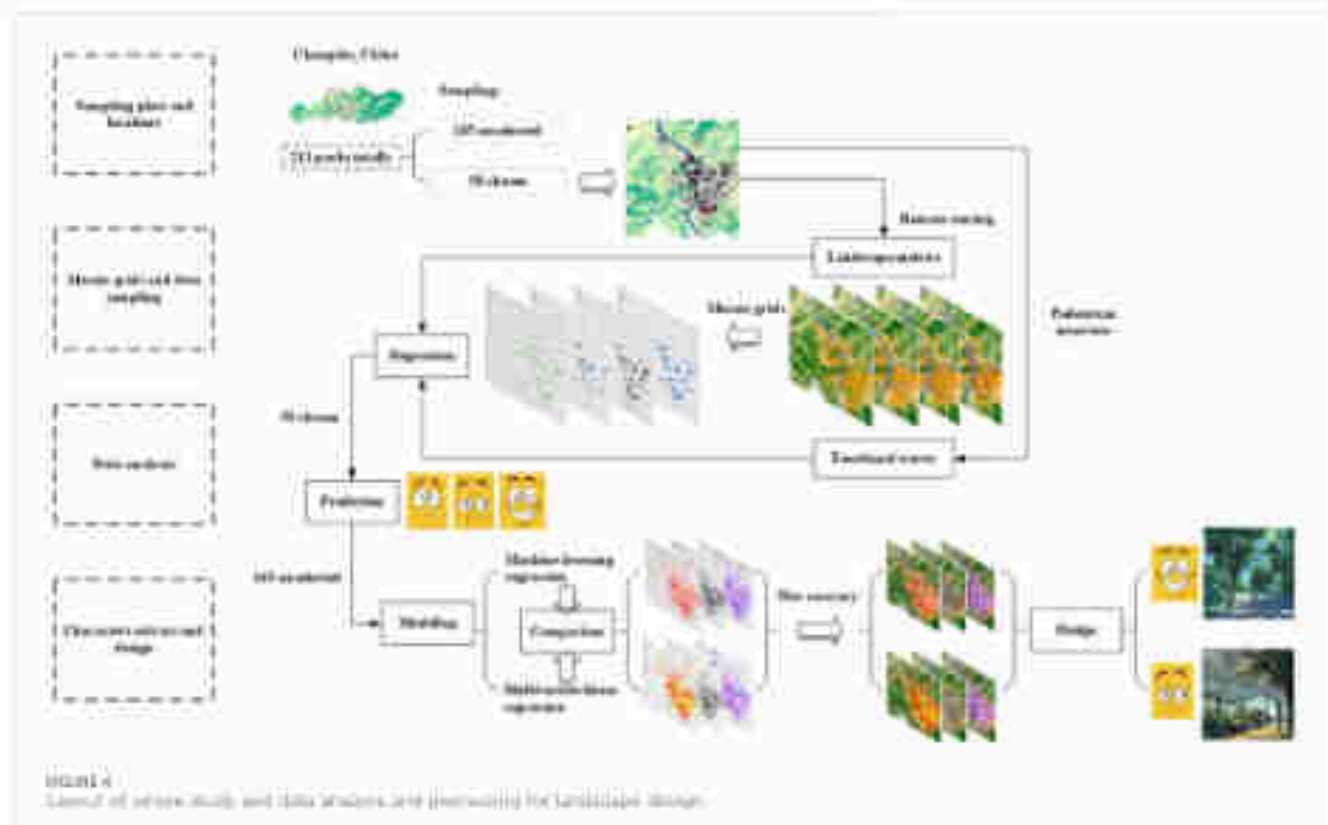


Figure 2
Typical recognition results of green view index (GVI) in urban parks of Changsha. Park names are derived from Table 1 and locations are referred to as green in Figure 1.

questionnaire, adapted from (Chambers & Green, 2013) and revised in a study (Gómez et al., 2014), included both consented participation and real-time interviews. Participants responded to 18 emotional descriptors, categorized into positive sentiments

like alertness, awe, amusement, joy, contentment, hopefulness, gratitude, love, and pride; and negative emotions such as disgust, anger, embarrassment, sadness, shame, fear, contempt, and anxiety. Responses were recorded in a binary format, with



0 and 1 representing 'no' and 'yes', respectively. Using these responses, emotional perceptions of connectedness with nature in urban parks were quantified using an emotional nonparametric relation index (ENRI) as shown in Equation 5 (Gao et al., 2024).

$$ENRI = \log \left(\frac{\sum_{i=1}^n Score_{+i}}{\sum_{i=1}^n Score_{-i}} \right) \quad (5)$$

where, $Score_{+i}$ and $Score_{-i}$ are totaling scores about binary perceived responses to positive and negative emotions, respectively, reported by the i th pedestrian up to the final j th per-park. Some pedestrians consented the participation, but neither responses included zero scores to any of emotions. This cannot be documented for recorded scores in next-step analysis.

Data of self-reported scores may contain bias caused by subjective interruption or uncontrolled systematic errors (Gao et al., 2022; Wei et al., 2021). Therefore, data were validated by calculating the matching accuracy and detecting correlation with data collected from a retest (Ma et al., 2021). The Cronbach alpha was calculated to be 0.903, which fell in the level that can be fully reliable for the acceptance of data in a low variance (Ma et al., 2021; Parry et al., 2011). Furthermore, self-reported data were validated with data from facial expression scores and Pearson correlation was calculated to be 0.57%. This also fell in the range that can be reliable that self-reported data can be reliable according to empirical values (Gao et al., 2024; Parry et al., 2011). Overall, our results can be fully reliable for their contribution to the estimate on nature connectedness.

2.4 Data process and case design

The layout of the entire study along with data statistics and processing are illustrated in Figure 4. Emotional results were averaged to derive mean scores for each selected park, alongside landscape metrics, which were mapped within the study area. Data extracted from selected parks were organized into mosaic grids, used for predicting emotional perceptions in other unselected park grids. All data underwent normality tests with consistent variances, allowing emotional scores to be analyzed for influencing factors from landscape metrics using multivariate linear regression (MLR). This analysis facilitated comparisons with prior studies on human emotional responses to Green and blue spaces (GBS) in urban parks (He et al., 2020a; Wei et al., 2022). Independent variables showing significant impacts on emotional scores were noted as references. Using data from various urban parks, landscape metrics were employed to enhance machine-learning models—specifically Random Forest (RF), AdaBoost, and gradient boosting trees (GBT)—for predicting emotional scores. Modeling accuracy was assessed using root mean squared error (RMSE), mean square error (MSE), mean absolute error (MAE), and determination coefficient (R^2). The importance of each landscape metric was evaluated across the three machine-learning models. Principal component analysis (PCA) was used to identify variation attributes of emotion and landscape data, aiding in comparing results between machine-learning models and MLR. The chosen model predicted emotional scores based on landscape metrics in grids of unselected parks. Green Vegetation Index (GVI) values were collected and averaged across all grids. These values were then mapped back onto land uses to display typical distributions of

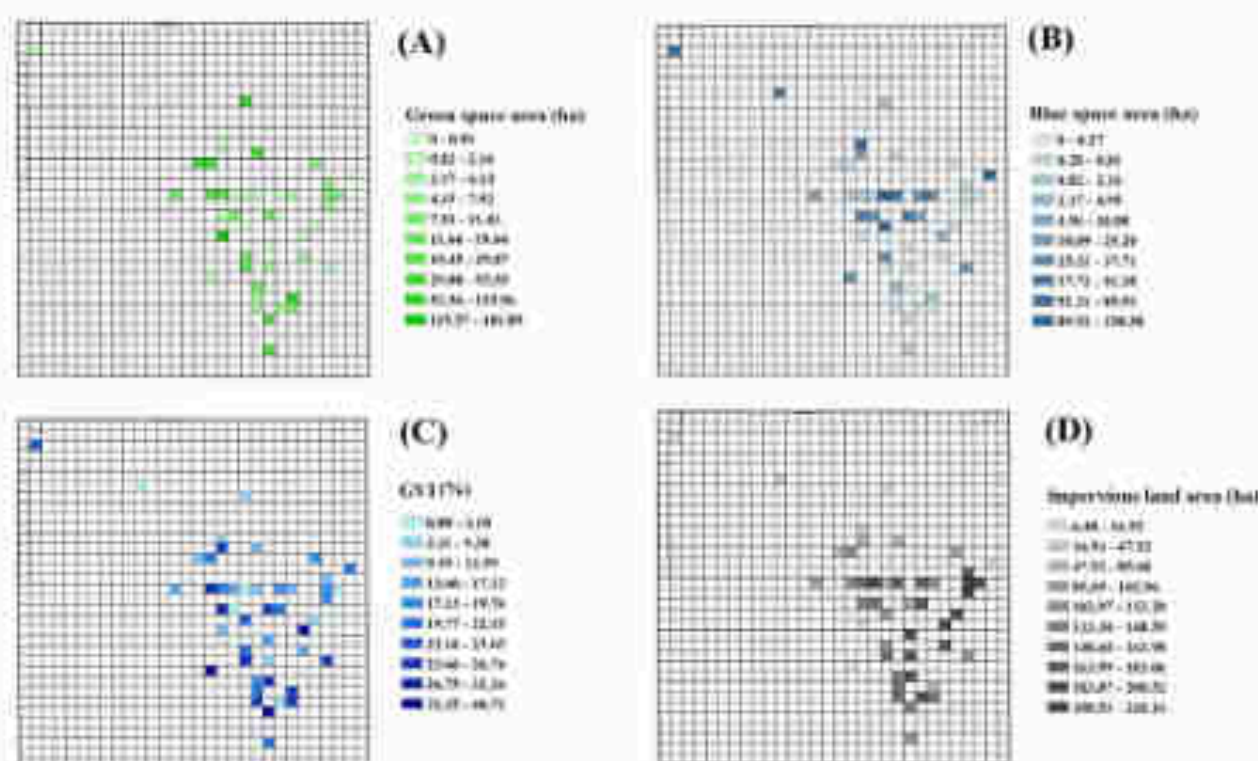


FIGURE 5
Spatial distributions of landscape metrics for urban parks in Changsha: (A) Green space area (ha), (B) Blue space area (ha), (C) GVI (%), and (D) Impervious land area (ha) in urban parks of study area of Changsha.

predicted emotional scores based on the number of selected parks (Table 1), typical parks with key landscape metrics that positively affect emotions were identified. These metrics were extracted and combined with regression results for use in designing with OpenAI (OpenAI, 2023).

3 Results

3.1 Spatial distributions of variables

Spatial distributions of landscape metrics for urban parks are depicted in *Supplementary Figure S1*, and mosaic grids in *Figure 5*. Parks in remote southern areas of Changsha, particularly GreenA, tend to be larger (*Figure 5A*). Conversely, BlueA does not follow this pattern and varies in size along the latitudinal gradient (*Figure 5B*). The Green Vegetation Index (GVI) is more uniformly distributed than GreenA and BlueA, with lower values in areas having higher proportions of impervious surfaces (*Figure 5C, D*).

The positive emotion score ranges from 1.33 to 6.60, averaging 4.95 ± 1.17 (\pm standard deviation), with higher scores in regions with larger green buffering spaces (GBS) (*Figure 6A*). The negative emotion score, with a lower average of 1.00 ± 0.62 (range: 1.00–3.33), is distributed more evenly (*Figure 6B*). The Emotional Normalized Ratio Index (ENRI) varies from -0.42 to 0.77 (mean: 0.41 ± 0.23), indicating a balance between positive and negative emotional perceptions, with higher positive scores

associated with GBS and negative scores linked to impervious surfaces (*Figure 6C*).

3.2 Multivariate linear regression estimate

The areal ratio of blue to green spaces (BlueG) and GVI both significantly contribute to the positive emotion score, although GreenA slightly reduces it (F value = 52.17, P-value < 0.0001, *Figure 7A*). Conversely, GVI and BlueG together have a substantial negative impact on the negative emotion score (F value = 14.28, P-value < 0.0001, *Figure 7B*). Both variables positively affect ENRI (F value = 47.79, P-value < 0.0001, *Figure 7C*).

3.3 Machine-learning modeling estimate

The performance of three machine-learning algorithms is presented in *Table 2*. The Gradient Boosting Tree (GBT) algorithm demonstrated superior performance compared to the others. Specifically, GBT achieved a higher coefficient of determination (R^2) in regression analyses. However, it registered higher values of root mean squared error (RMSE), mean square error (MSE), and mean absolute error (MAE) when predicting negative emotion scores than the Random Forest (RF) algorithm. Despite this, the regression errors for GBT were generally better controlled compared to those for AdaBoost. Consequently, GBT was selected for further analysis in regression modeling.

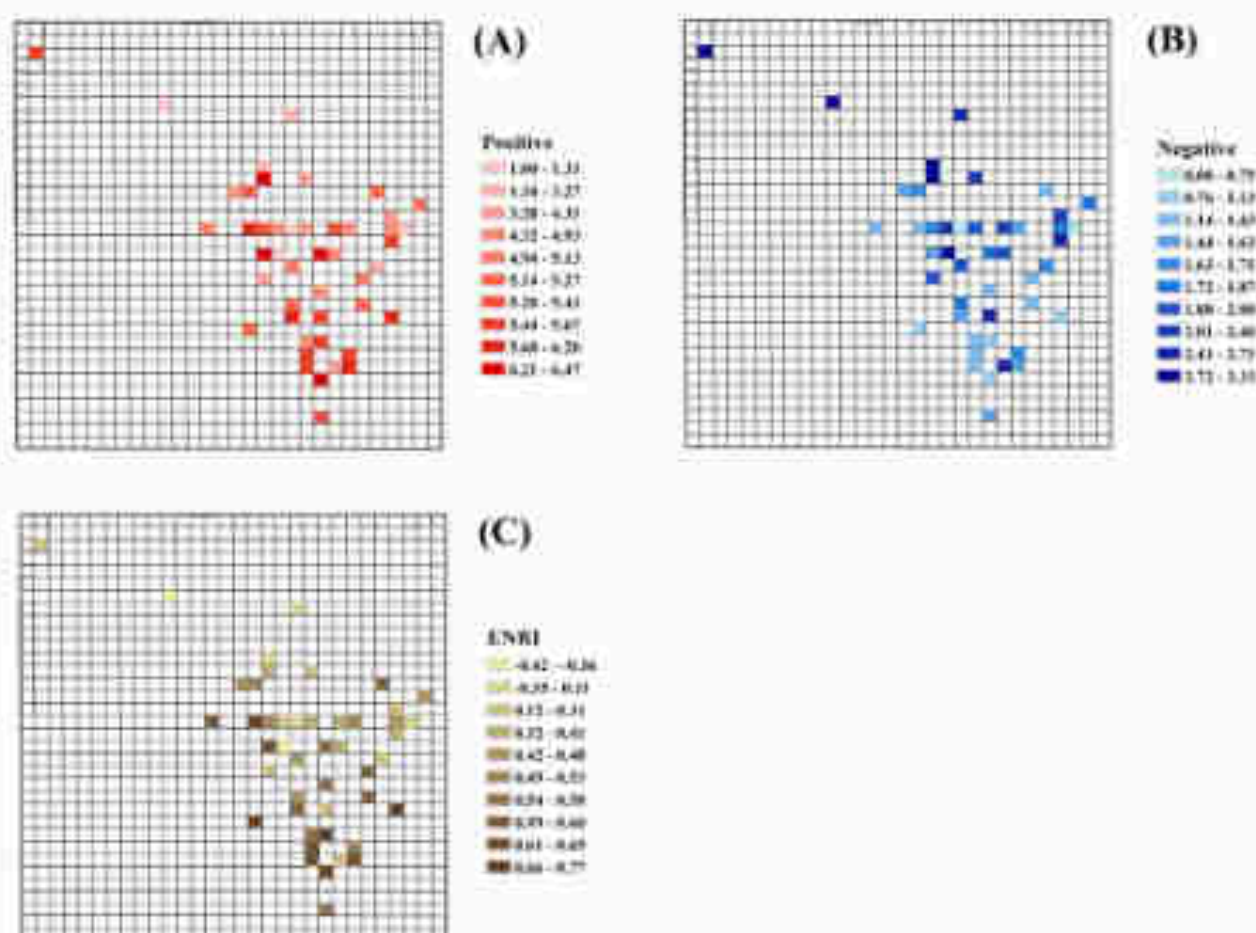


FIGURE 6
Spatial distribution of emotion scores for positive (A) and negative (B) emotion scores and ENRI (C) in 165 parks of Changsha.

Regression analysis using GBT highlighted the significance of various landscape metrics on emotional scores. Metrics such as the area of green and blue spaces (GandB), park area (ParkA), the ratio of green space to impervious surfaces (Grbf), the ratio of impervious surface area to host park (ImpR), GreenA, and the Green Vegetation Index (GVI) were identified as significantly influential (Figure 5). Positive emotion scores correlated strongly with GVI in specific park grids (Figure 8A). Negative emotion scores were influenced by contributions from GandB, ParkA, GreenA (feature importance: all >0.2), and GVI (feature importance: 0.18) (Figure 8B). The Environmental Naturalness Related Index (ENRI) was primarily influenced by GreenA and GVI, both showing feature importances of >0.2 (Figure 8C).

3.4 Principal component analysis verification

The first two principal component analyses (PCAs) accounted for 56.17% of the cumulative eigenvalues, with the first PCA comprising 32.25% and the second 23.92% (Figure 9). Consequently, these two PCs represented over 50% of the data variation, with the first PCA proving more reliable for capturing data variation. The eigenvalues for the positive emotion score and

ENRI followed a similar vector trend as the negative emotion score. The landscape metric of ImpR displayed a trend similar to that of the negative emotion score, both diverging from those along the first PC axis for ParkA, GandB, GreenA, Grbf, and GVI. These metrics were identified by the GBT algorithm in the machine-learning model (Figure 4), but were not detected by MLR (Figure 7). Parameters detected by MLR included ImpG and ImpB, which aligned with eigenvalues along the second PC axis, yet exhibited weaker trends against GVI and GreenA. Therefore, MLR only identified two parameters (GreenA and GVI) that aligned with trends in positive emotion score and ENRI. It also identified two other parameters unrelated to emotion scores. Overall, machine learning regression using the GBT algorithm outperformed MLR in modeling emotions related to landscape metrics.

3.5 Location-based emotion distribution overlapping land uses

According to gradient boosted trees (GBT) modeling, it is possible to predict emotional scores for the remaining 165 unselected parks. The spatial distribution of these scores

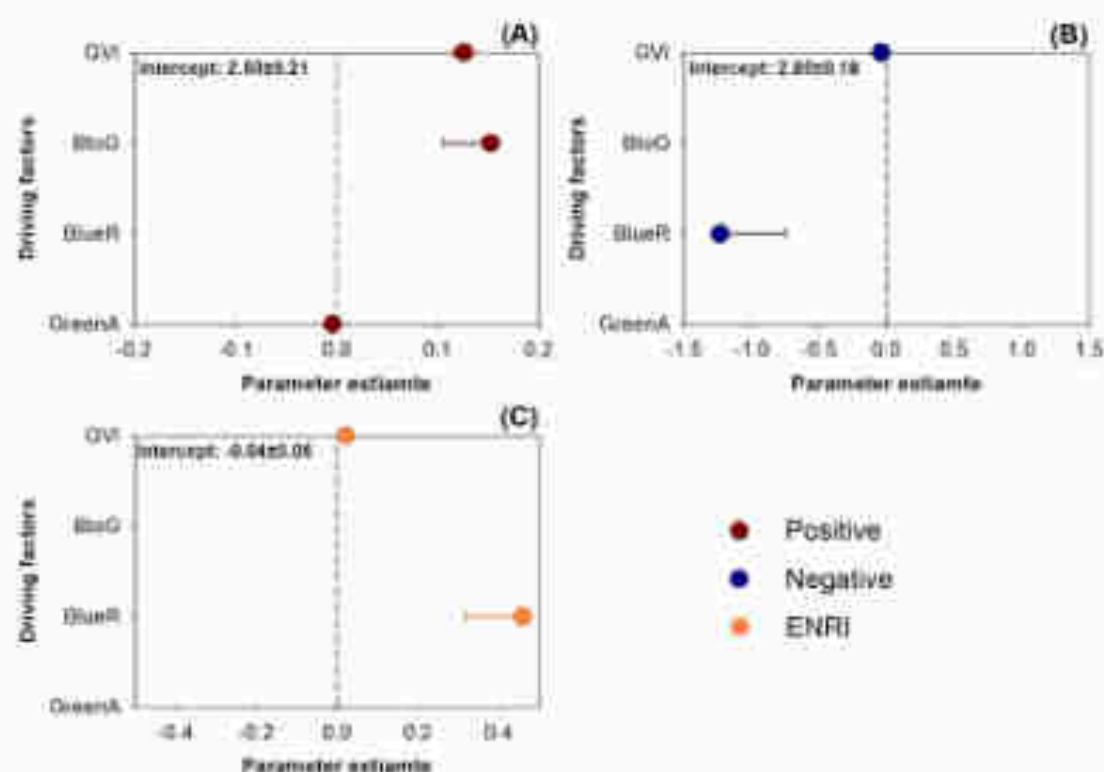


FIGURE 2

Relationships between regression of positive (A) and negative emotion scores (B) and ENRI (C) against landscape metrics of green space and GreenA. Blue space area ratio of built-up area (BlueR), area ratio of blue to green space (BlueO) and QV. Error bars represent standard errors derived from data sets.

TABLE 2 Comparison of regression performances using three machine-learning modeling algorithms for positive and negative emotional indices and ENRI.

Target variable	Model	R ² MSE ^a	R ² RMSE ^b	MAE ^c	R ² d
Positive	Random Forest	0.5848	0.5564	0.0792	0.7533
	Adaboost	0.6787	0.4719	0.0475	0.8934
	Gradient Boosting Trees	0.7267	0.4484	0.1152	0.9064
Negative	Random Forest	0.0076	0.3376	0.0086	0.7163
	Adaboost	0.0323	0.2838	0.0075	0.6973
	Gradient Boosting Trees	0.0373	0.2885	0.0068	0.5908
ENRI	Random Forest	0.1089	0.0282	0.1127	0.6679
	Adaboost	0.1463	0.0197	0.1065	0.5526
	Gradient Boosting Trees	0.1114	0.0288	0.1061	0.5849

Note:

^aMSE, root mean-squared error.

^bRMSE, root mean-squared error.

^cMAE, mean absolute error.

^dR², coefficient of determination.

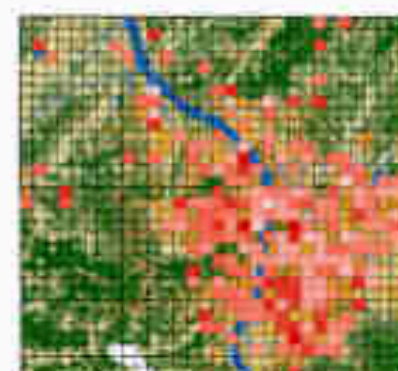
across all 185 parks is illustrated in [Supplementary Figure S4](#). Additionally, grid distributions were superimposed on land uses, and the overlapping results are presented in [Figure 10](#). When compared with multiple linear regression (MLR) results, the GBT model shows that high positive emotion scores are predominantly

found in the southern built-up areas of Changsha, with occasional high scores in the northern parts as well ([Figure 10A, B](#)). Conversely, higher negative emotion scores are predicted by GBT in the eastern part of the study area, where MLR shows significantly fewer high values ([Figure 10C, D](#)). GBT also suggests that high

Machine-learning regression



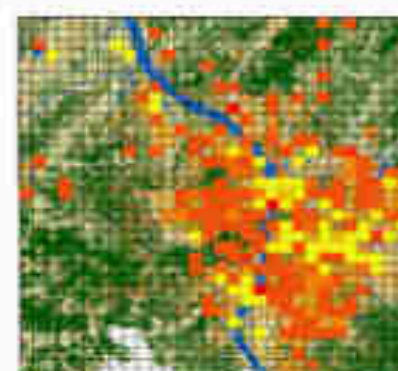
Multivariate linear regression



(A)

Positive

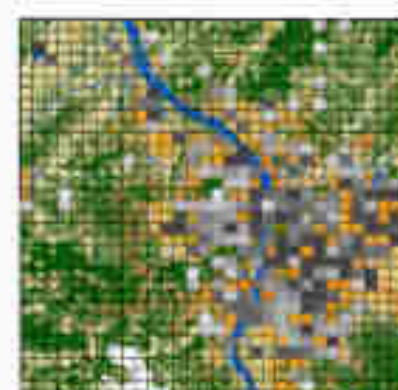
0.00 - 0.25
0.26 - 0.51
0.52 - 0.77
0.78 - 1.03
1.04 - 1.29
1.30 - 1.55
1.56 - 1.81
1.82 - 2.07
2.08 - 2.33
2.34 - 2.59



(B)

Positive

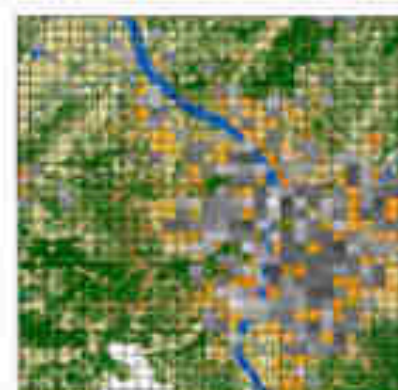
0.00 - 0.75
0.76 - 1.50
1.51 - 2.25
2.26 - 3.00
3.01 - 3.75
3.76 - 4.50
4.51 - 5.25
5.26 - 6.00
6.01 - 6.75
6.76 - 7.50



(C)

Negative

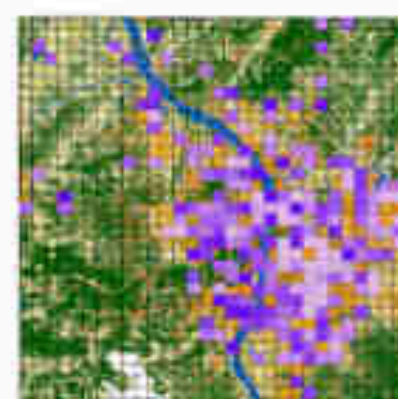
0.00 - 0.49
0.50 - 0.99
1.00 - 1.49
1.50 - 1.99
2.00 - 2.49
2.50 - 2.99
3.00 - 3.49
3.50 - 3.99
4.00 - 4.49
4.50 - 4.99



(D)

Negative

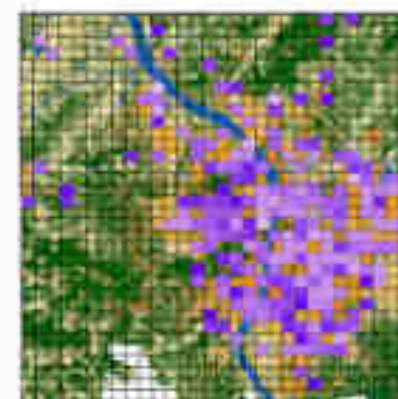
0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.25
1.26 - 1.50
1.51 - 1.75
1.76 - 2.00
2.01 - 2.25
2.26 - 2.50



(E)

ENRI

0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.25
1.26 - 1.50
1.51 - 1.75
1.76 - 2.00
2.01 - 2.25
2.26 - 2.50



(F)

ENRI

0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.25
1.26 - 1.50
1.51 - 1.75
1.76 - 2.00
2.01 - 2.25
2.26 - 2.50

Legend

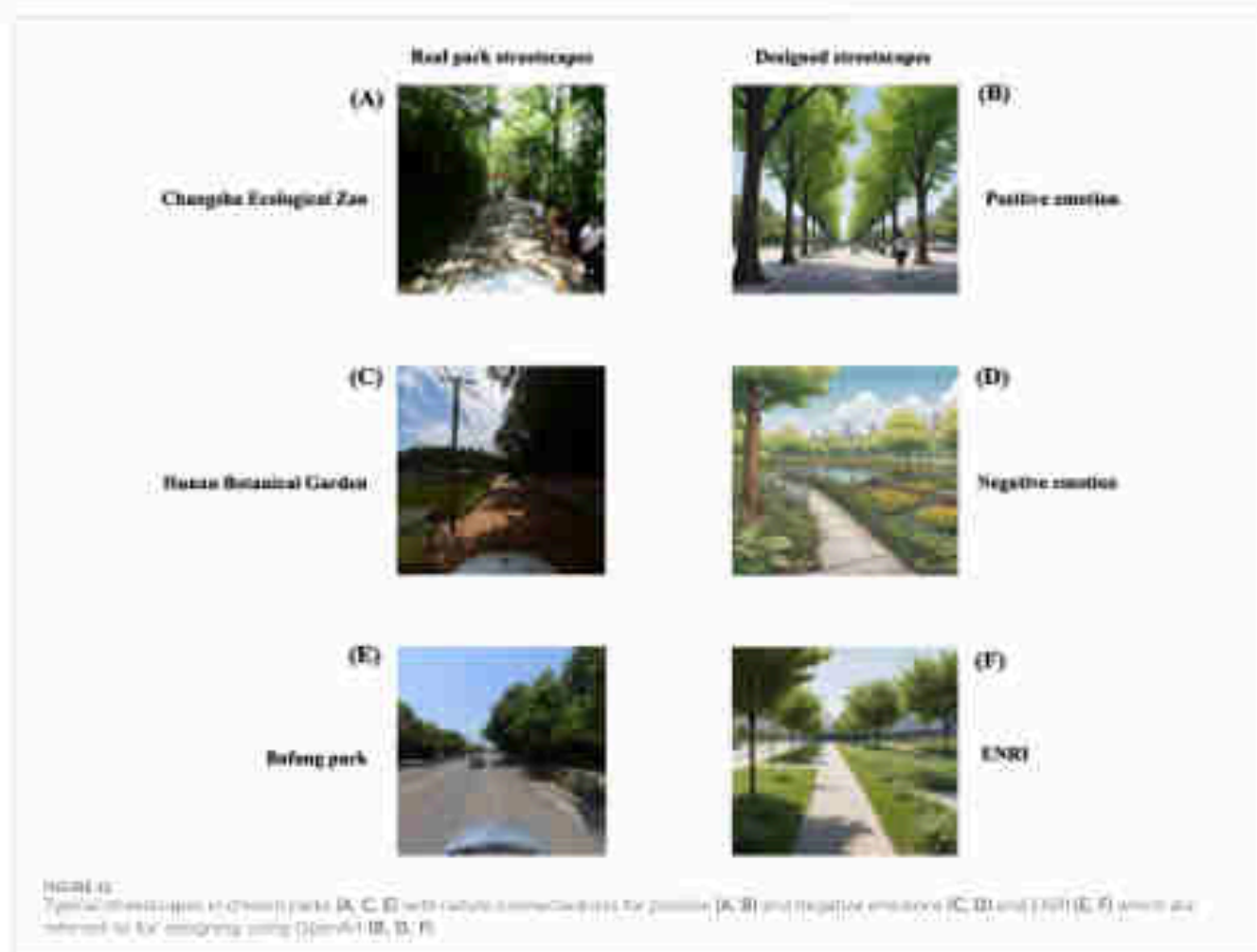
Green space
Blue space
Impervious surface

0 5 10 20 Kilometers

FIGURE 4
Spatial distribution of positive (A, B), negative (C, D), and ENRI (E, F) in grids of all parks over land study in Chengdu City expressed by machine-learning GBT model (A, C, E) and multivariate linear regression (B, D, F).

The Human Botanical Garden is identified by GBT as typically evoking negative emotions (Figure 1; Number 44, Table 1). This response is primarily due to extensive areas of dwarf plants on lawns, grasslands, and near water bodies, which result in a low GVI with visible buildings (Figure 4(C)).

"Driven in an overall comic style about shrubs and weeds visible behind iron fences of a large urban park, large areas of lawns and wetland can be seen clearly inside the park, where no tree can be seen. Plants are mainly in species of ferns, flowers, and saplings. Although landscape inside the park looks enriched with greenery and



waterbody, most plants are dwarf both on land or in wetland and rare of plants on ground account for occupation of visual view which is full of blue sky and white cloud.”

The design can be seen in [Figure 11G](#).

ENRI reflects a complex blend of positive and negative emotions, typically experienced in Rufang Park ([Figure 13](#); Number 18, [Table 1](#)). This park is characterized by large open green spaces with moderate to high GVI levels, and buildings visible in the distance ([Figure 11E](#)). This setting can be used to prompt further analysis.

“Drawn in an overall comic style. Large areas of forested lands are distributed in a wide range across areas across black color iron fences of an urban park. Trees are mostly planted in lines both inside the park and along a sidewalk outside park’s iron fences. Most lands outside the park fences are covered by lawns, meadows, and grasslands. Trees have large canopies in fresh green color in nearby position with shadows at further places. Large canopies are connected together to account for about 50% of visual view in a streetscape along park’s fences. A waterbody can be seen behind greeneries. The waterbody is a wetland with scattered green plants over and blue water surface behind shrub plants. The floor is mainly covered by grassland and lawns and nearly no impervious path or road can be seen.”

The design can be seen in [Figure 11H](#).

4 Discussion

4.1 Connectedness of perceived emotions

The concept of natural connectedness is significant for the level of nature perceived and the corresponding emotional responses in humans ([Damenelli-Urrea et al., 2023](#)). This is evident in how humans emotionally react to landscapes with measurable amounts of nature ([Garcia et al., 2024](#)). In our study, we measured perceived emotions using the emotion-nature ratio index (ENRI, calculated as the logarithm of the ratio of positive to negative emotion scores). Over 90% of ENRI values were positive, reflecting a higher report of positive emotions compared to negative ones. This finding aligns with observations in naturally preserved parks in southeastern Spain ([Garcia et al., 2024](#)) and in coastal protected areas of the same region ([Damenelli-Urrea et al., 2023](#)). Thus, human physiological parameters were more suitable to be used for evaluating restorative effects than psychological factors ([Jin et al., 2018](#); [Wu et al., 2023](#); [Yu et al., 2016](#)). Our self-reported data were detected to have an acceptable correlation with facial expression scores, and the latter was attracting an accumulating number of followers who together gave a higher reliability than the earlier one ([Wang L. F. et al., 2023](#); [Jin et al., 2020](#)). Other research utilizing facial expression scores also found predominantly positive

emotional responses at city (Wu et al., 2021a), regional (Zhong et al., 2021), and national levels (He et al., 2023b). These results support theories such as stress recovery theory (SRT) and attention restoration theory (ART), suggesting that people tend to experience more positive emotions when they feel a connection to nature. Conversely, artificially built environments, like those with extensive greenery in greenhouses, were linked to more negative emotional responses (Liu et al., 2024; Odeh et al., 2023). In our research, ENRI was particularly significant in park landscapes with large green spaces and high green view index (GVI). Cross-city studies in heavily built environments have supported these findings (Wu et al., 2021b; Yu et al., 2018), suggesting the benefit of designing landscapes within buildings that promote a strong connection to nature, as assessed using ENRI.

4.2 Landscape metrics that contribute to emotional perceptions

The MLR results showed that BlueR significantly contributed to ENRI by reducing negative emotion scores. Additionally, increasing BlueG's contribution could enhance positive emotions. Surprisingly, GreenA had a minimal and negative impact on positive emotion scores and showed no significant contributions to ENRI. PCA verification suggested these findings were largely unreliable due to their irrelevance to emotional scores. These metrics had strong individual correlations with emotional scores, but their interactions were nullified when contradicted by collinearity issues. Machine learning regression models, which do not rely on linear relationships, do not face these collinearity problems. It is realistic to face challenges to increase the ratio of BlueR in urban landscape which may need decreasing ratio of GreenR. Stand area and municipal input will be two solid obstacles to achieve these benefits.

Generally, GRS represent a significant portion of accessible nature in urban parks. Research suggests that the combination of GRS plays a more critical role in enhancing positive emotions than either green or blue spaces alone (Wang & Y. et al., 2022). Studies also indicate that urban blue spaces are as beneficial as green spaces for mental wellbeing (Heldrich et al., 2019; Vervaeke and Kuitert, 2015). Specifically, green spaces are more beneficial for positive emotion in downtown areas with scattered, small patches, while blue spaces enhance positive emotions in remote, rural areas with large, continuous bodies of water (Wu et al., 2021a). In Changsha, the Xiang River flows through the city in a latitudinal direction, branching into several waterways in built-up downtown areas (Figure 1, 2). Here, large green spaces are fragmented into smaller, scattered patches. Parks near these blue spaces attracted volunteers who reported both positive and negative emotions, with a predominance of positive ones. According to GBT machine learning results, blue spaces had little direct impact on emotions but helped to integrate a network of green spaces and impervious surfaces. Buildings in these landscapes, characterized by extensive green spaces but sparse vegetation, primarily influenced feelings of sadness and reduced positive emotions.

In landscape metrics, the GVI significantly contributes to the perception of positive emotions, demonstrating that the amount of visible greenery in a streetscape is crucial for feeling connected with

nature. This aligns with the findings of Huang et al. (Huang et al., 2022), who suggested that the ability to physically interact with greenery is more significant for fostering positive sentiments than merely having access to large green areas. Additionally, parks located in regions with extensive impervious surfaces, such as densely packed roads, typically display high Emotional Nature Relatedness Index (ENRI) values. This suggests that GVI, when accessible, can enhance positive emotions.

The methodology of multiple linear regression (MLR) significantly differs from that of logistic regression in machine learning modeling. The gradient boosting trees (GBT) algorithm highlighted the beneficial effects of green spaces on emotional wellbeing, findings that were supported by principal component analysis (PCA). Similarly, Huang et al. (Huang et al., 2022) found that both the size and GVI of green spaces are crucial for the positive emotional responses of visitors to urban parks in Hubei. Sun et al. (2023) also observed that employees exhibit more positive emotions in workplaces (Sun et al., 2021; Wu et al., 2024) with large green spaces and high GVI. Moreover, noted that high-GVI environments can enhance thermal comfort by moderating increases in systolic blood pressure and heart rate, changes that are associated with positive emotional responses to green spaces, as confirmed by (Wang et al., 2023; Yu et al., 2018). Overall, contact with green spaces, whether vertically or horizontally oriented, is important for feeling connected to nature (Vervaeke et al., 2019). GBT-based machine learning models can more accurately represent these effects compared to MLR.

4.3 Discrete results between MLR and machine-learning modeling

Two regression systems demonstrated both divergence and similarity in their findings. The most notable divergence was observed with GreenA, which the multiple linear regression (MLR) suggested negatively influenced the perception of positive emotions. However, the Gradient Boosting Tree (GBT) algorithm identified GreenA as having high feature importance for positive emotions. This discrepancy arose from the technical limitations under general linear model (GLM) rules, where GreenA was impacted by its collinearity with the coefficient BlueG. BlueG strongly influenced the positive emotion scores, stemming from its impact on negative emotion scores. Collinearity typically results in high mean squared error (MSE) in regressions (Huang, 2024), and GLM lacks mechanisms to eliminate such errors. Conversely, machine learning models, including GBT, are less affected by multicollinearity due to their complex architectures, which optimize procedures to control or reduce root mean squared error (RMSE), including strategies to exclude multicollinear data (Chen et al., 2022) inputs. This explains why variables like BlueG were not selected for the GBT model. Another divergence involved GVI, which MLR estimated as a driver of positive emotion scores and negatively impacted scores in the GBT model. Although it is possible for highly greened streets to evoke negative emotions, this is less likely to occur frequently, as MLR suggested. The GBT model indicated that while negative emotions could be perceived on high GVI streets, it happened with lower probability compared to positive emotions, leading GBT to assign high feature importance to GVI.

This rationale applies similarly to GreenAI's contrasting results in MLR and GBT, showcasing that machine learning models often deploy more objective strategies to handle errors and assess emotional impacts compared to MLR.

4.4 Theoretical base for cases of design

The case of design in our study was generated on the basis of findings and inner relationships between human emotions and perceptions to the nature in parks. These results can have more practical implications than just being an exhibition of modelling results. At the regional scale, our design disagreed with a rule that was about to be recommended that the higher dose of nature in environment the more positive sentiments can be perceived (Liu et al., 2021b; Zhang et al., 2021). Our results, however, showed that regions with high doses of nature in ambient environments can evoke high scores of ENRI, but this accuracy was lower than results found in regions with larger areas on impervious lands. Hence, in the meaning of urban planning high dose of nature should be considered more in the design of built environment if positive sentiments were achieved in mind of visitors. This can be explained by the SRT theory as people living in cities tended to attract more mental stresses; hence they may perceive higher restorativeness when facing the nature compared to those living in remote rural regions. Secondly, studies on horizontal planes of GBS appeared to demonstrate that a large area of nature can precondition the perception of positive emotions (Jiang et al., 2022; Liu et al., 2021b; Naeemali et al., 2022; Wang and Xiao, 1997). In design, however, the visible parts of green nature can function to elicit positive emotions rather than a large and flat space with low occupation of visible view by greenery. This is important for landscape architecture to arrange the trade-off of touchable nature in greenery between horizontal and vertical planes. This can reflect outcomes ruled by the AIT theory, which asserted that only the touchable nature can attract and recover attention. Finally, the ratio of visible green in landscape was indicated to be a stronger factor in the design to attract positive emotions rather than other types of nature. This can be referred to by policymakers to consider a higher use of trees with large canopies along streets and large urban wetland parks should not be encouraged actually.

4.5 Limitations of this study

Our study has three limitations. Firstly, Changsha lacks significant elevation variation, which may explain why elevation did not influence human emotions in urban parks. Studies in other cities have suggested that elevation can impact park visitors' emotions (Lu et al., 2018; Wang and Phau, 2022; Zhang et al., 2021). Further work is essentially needed to repeat our study in more cities as variances may impact results found in a single city through varied cultural and environmental factors among different cities. Therefore, conducting our study in a different city might reveal elevation effects on emotions. Secondly, the emotion scores were assessed using a methodology previously employed in various studies (Gao et al., 2024; Shamsoddin et al., 2017), that have been validated and passed tests in our study. This

methodology was not perfect because our data were collected in a spontaneous and parks' tourism may be limited to a special set of emotions at this time of year. More time courses or seasons are suggested to be tested in further works to promote the power of usage. Thirdly, we found that machine-learning algorithms could predict emotion scores with determinant coefficients over 50%, a threshold acceptable for predictive studies. Even so, the employment of deep learning algorithms may face challenges from overfit. Nevertheless, the RMSE and MSE values were often higher than 0.1, suggesting that increasing the data input could help minimize systematic errors. That is why we showed and compared predictive results and mapped results together to show similarities of results indicated by GBT and MLR. Future studies should explore more machine-learning models to optimize these regressions. Additionally, we designed a landscape embedding natural elements using the OpenArt AI tool. This approach was not widely accepted, indicating that it might be more effective to compare AI-designed landscapes with those designed using traditional artistic methods.

5 Conclusion

In pursuit of a sustainable GBS landscape that enhances perceived emotions in urban parks, we moved beyond traditional multiple linear regression (MLR) and applied selected machine-learning algorithms. The machine-learning GBT regression, validated through PCA, proved superior to MLR. It highlighted the significant influence of green space connectivity on positive emotions and the impact of impervious surfaces on negative sentiments. The results demonstrated that landscapes promoting positive emotions typically featured high Green View Index (GVI) along streets bordered by large, open green spaces. As used for cases of planning and designing, built environments in municipal areas on impervious surfaces can be employed for inducing more positive sentiments of visitors due to perceptants of more closeness with nature. Large areas of green and blue spaces may not be so needed for people who were seeking for restorative environments. High dose of blue space in the nature and high occupation of sight view were strongly suggested to inducing stronger positive sentiments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by School of Humanities and Arts, Hunan International Economics University (Reference code: 20240523JHT). The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because Consented orally by volunteers.

Author contributions

RZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing—original draft. JR: Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing—review and editing.

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References

- AA, B. Y., Wang, D., Liu, X. J., Guan, H. M., Wei, H. X., and Ren, X. R. (2019). The effect of environmental factors on urban tourists' on travel pressure and heart rate in extremely tourism. *J. Tour. Res.* 24(1), 27–34. doi:10.1080/13440009.2018.1540144
- Anderson, M. B., Bates, A., and Oroszko, G. (2019). Designing urban green (re)connections for mental health and elderly wellbeing. *Sustainability* 11(1), 323. doi:10.3390/su11010323
- Beggs, P. J., Patel, K. M., Madhavan, M. A., Sorn, S., Sharma, N., Kulkarni, S. M., et al. (2022). Machine vision-based gradient-boosted tree and support vector regression for real-life production-to-learning. *Int. J. Adv. Manuf. Technol.* 123, 471–485. doi:10.1007/s00170-022-11137-2
- Cameron, E. W. F., Brindley, P., Moore, N., McEwen, E., Ferguson, E., Balfanz, D., et al. (2020). Where the wild things are: Do urban green spaces with greater animal biodiversity promote more positive emotions in humans? *Urban Ecosyst.* 22(2), 91–117. doi:10.1007/s11252-020-09254-3
- Chen, J. Y., Liang, X. M., Ren, X. Y., Cheng, W. K., Pheng, S. W., Hong, Z. W., et al. (2022). Integrating the multi-objective problem and its machine learning approach: a review. *Sustainability* 10(8), 1243. [Online]. doi:10.3390/su10081243
- Chen, C. H., and Fan, P. (2022). Can urban residents perceive green and blue space in residential as joyful sentiment? A validation in wenzhou, China. *Front. Psychol.* 13, 8421. doi:10.3389/fpsyg.2022.8421
- Chen, C. H., Li, H. W., Fan, P., Lin, H., Yao, J., Wu, L. P., et al. (2022). Predicting the effect of street environment on residents' travel mode in large urban areas using machine learning and street view images. *Int. J. Geogr. Inform. Sci.* 36(10), 1915. doi:10.1080/10897647.2022.2104405
- Chen, L., Lu, Y., Sheng, Q., Fu, Y., Wang, R., and Xu, Y. (2020). Estimating pedestrian volume using Street View images: a large-scale validation test. *Geoper. Environ. Urban Sci.* 4(1), 101440. doi:10.1016/j.geosusci.2020.101440
- Citicipedia Database (2020). Semantic understanding of urban street scenes. Available at: <https://www.citicipedia-database.com/Citicipedia-Archive> [12, 2022].
- Dewon, L., Eshelbar, M., van Ernd, L. E. E., Chaw, J., Ogras, T. F., Scheller, C., et al. (2023). Why don't we go outside? Perceived constraints for users of urban green space in London. *Urban Res. and Urban Econ.* 12, 127940. doi:10.1016/j.urue.2023.127940
- Dewon, L., Eshelbar, M., Yamasaki, T., van Ernd, L. E. E., Johnson, S. E., and Scheller, C. (2024). Urban green space for social integration: which types of green space drive inclusion and why? *Urban Res. and Urban Econ.* 13, 128418. doi:10.1016/j.urue.2024.128418
- Du, H. Y., Gu, Y. L., Zhou, P. Q., Jin, H., Jiang, W. Y., and Xu, Y. Q. (2019). Urban blue-green space planning based on thermal environment simulation: a case study of Shanghai, China. *Land Use Policy* 181, 104301. doi:10.1016/j.landusepol.2019.104301
- El-Hachimi, L., Du, Y., Fan, P., Vitor, M., Lisk, A., and Corral, C. (2022). Mapping potentially green/blue dependent vegetation in the Mediterranean basin using global

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenv.2024.1440101/full#supplementary-material>

- product mapping via satellite and vegetation characteristics. *Int. J. Geogr. Inform. Sci.* 36(10), 1915. doi:10.1080/10897647.2022.2104405
- Fang, X. Y., Qi, Y., Huibin, M., Guo, T., and Jia, L. (2024). Do urban green spaces have any effect on the health of urban residents? *J. Environ. Develop. Sustain. Manag.* 16, 102728. doi:10.1080/10897647.2024.2387228
- Fu, H. P., Liu, J., Dong, X. Y., Chen, Z. L., and Shi, M. (2024). Evaluating the sustainable development goals within urban planning for decision-making: a major transition-oriented urban planning strategy in China. *Land* 13(1), 190. doi:10.3390/land13010190
- Gao, S., Riquelme-Sanchez, J. M., Quintanilla-Soriano, C., Lopez-Salazar, H. D., Chacón-Ure, L., Ojeda, M., et al. (2020). A methodological approach to integrating human emotions in post-occupancy evaluation: insights from 44 Spain. *Build. Environ.* 184, 107498. doi:10.1016/j.buildenv.2020.107498
- Gao, H. M., Wu, H. X., Han, S. J., and Gu, P. (2021). Factors associated with green people exposed to constructed urban forest canopy: subjective and objective assessment. *Int. J. Environ. Res. Public Health* 18(12), 6222. doi:10.3390/ijerph18126222
- Hao, N. Y., Li, X. Z., Han, D. P., and Xu, W. B. (2024). Quantifying the impact of street greening during hot and seasons on emotional perception: guidelines for residents well-being. *Front. Psychol.* 15, 119. doi:10.3389/fpsyg.2024.119
- Hu, Q., Wang, Y., Qiu, Q., Yu, Y., Wang, Z., Wu, H. X., et al. (2023b). Joint effects of air PM_{2.5} and microclimate dimensions on mental symptoms of urban green space visitors in city-dwelling population urbanization: a pilot study on 30 cities of East China. *Int. J. Geogr. Inform. Sci.* 37(10), 107498. doi:10.1080/10897647.2023.2246257
- Hu, Q., Wang, Y., Qiu, Q., Yu, Y., Wu, H. X., and Li, Y. (2023a). Perceived sentiment toward urbanization in degraded forests are shaped jointly by landscape attraction and microclimate. *Transp. Res. Part C Emerg. Technol.* 144, 104115. doi:10.1016/j.trc.2023.104115
- Huibin, M., Guo, T., Lin, Y., Zhang, J. H., Gu, P. H., and Wang, S. Y. (2019). Using deep learning to estimate street view green and blue space and their association with positive depression in Beijing, China. *Environ. Sci. Data* 1, 107–117. doi:10.1038/s43593-019-0010-1
- Huang, B. D., and Tian, X. L. (2021). Screen-selecting-based urban green space detection using machine prediction algorithm optimized machine learning approach. *Math. Problems Eng.* 2021, 1–12. doi:10.1155/2021/7106001
- Hui-Huang, W., and Burchell, B. (2022). Does public space have to be green to improve well-being? An analysis of public space across Greater London and its associated subjective well-being. *Cities* 125, 103760. doi:10.1016/j.cities.2022.103760
- Jiang, X. K., Li, S. W., Li, H. H., and Tian, M. (2019). Impact of landscape structure and tree space on urban green space on subjective well-being. *Sustainability* 11(1), 439. doi:10.3390/su11010439
- Jiang, Y. Y., Zhu, J. J., Zhu, B. R., Wang, Y., Wu, H. X., Xu, Z. H., et al. (2022). Environmental perceptions of public green spaces on the happiness of green space: A verification in wenzhou, China. *Front. Psychol.* 13, 1132. doi:10.3389/fpsyg.2022.1132

Urban Green Experience. *Urban For. and Urban Green.* 18, 126496. doi:10.1016/j.ufug.2020.126496

Wen, Y., Gu, X. R., Deng, W. J., Zou, Q., Hu, Y., Sun, Q., et al. (2015). The effects of dynamic and static visual loading (Shanhu-schi) on physiological and psychological health in males and females. *Forest* 14 (9), 1792. doi:10.3390/f9091792

Wu, L. J., Deng, Q. D., Liu, S. X., Jiang, W. Y., Hu, M., and Chen, Q. B. (2021). Effects of spatial stimulus of urban landscape forms on the restoration potential and preferences of adolescents. *Land* 11 (12), 1340. doi:10.3390/land11121340

Xiang, Y., Hedderley, M., Wang, S., Qiu, L., and Guo, T. (2021). Reducing subjective crowding and visual perception of urban green spaces. *Ecol. Indic.* 127, 108772. doi:10.1016/j.ecolind.2021.108772

Xu, B., Zhu, G., Gong, L., and Liu, Y. (2014). Emotional perceptions of thermal comfort for people exposed to green spaces characterized using microclimate in urban parks. *Land* 3 (9), 1547 (Online). doi:10.3390/land3091547

Xu, H. Q. (2019). Analysis of improvement surface and its impact on urban form development using the normalized difference urbanness index (NDUI). *Phragmenia* Eng. Resour. Sci. 28 (5), 377–383. doi:10.14358/pes.28.5.377

Yu, C. P., Lu, S. S., and Guo, X. Y. (2014). The effect of territoriality, forest and urban environments on physiological and psychological responses. *Urban For. and Urban Green.* 11, 104–114. doi:10.1016/j.ufug.2013.06.003

Zhang, J., Tang, Z., Chen, X., Guo, M. Y., and Guo, P. (2011). Optimizing urban form landscape for better perception of positive emotions. *Forest* 11 (10), 1691. doi:10.3390/f11101691

Zhang, L., Tang, Z., Wu, T. X., Xu, Z. H., Hu, C. P., and Guo, P. (2013). Expressing urban forms for mitigation of negative emotion of people exposed to seasonal PM_{2.5} in Northeast China. *J. For. Res.* 34 (3), 2345–2361. doi:10.1007/s11079-012-9190-x

Zhang, P. R., and Tang, Z. X. (2015). A robust Adaboost-ET based ensemble extreme learning machine. *Math. Problems Eng.* 2015, 1–11. doi:10.1155/2015/264670



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Public health perspectives on green efficiency through smart cities, artificial intelligence for healthcare and low carbon building materials

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Introduction: Smart cities, artificial intelligence (AI) in healthcare, and low-carbon building materials are pivotal to public health, environmental sustainability, and green efficiency. Despite their critical importance, understanding public perceptions and attitudes toward these domains remains underexplored. Additionally, the effective use of advanced technologies like convolutional neural networks (CNN) in predicting and promoting low-carbon solutions in construction is gaining attention.

Methods: This study employs a dual approach: (1) A survey of 200 respondents was conducted to gauge public perceptions and attitudes toward smart cities, AI in medicine, and low-carbon building materials. (2) A CNN model was developed and implemented to predict the performance of low-carbon building materials. The model utilized convolutional and pooling layers to capture local features and spatial information from image datasets, with tasks including image classification and segmentation.

Results: The survey results indicate high awareness of smart cities (80%), with 60% associating them with environmental protection and green living. For AI in medicine, 70% of respondents are aware of its applications, but only 45% perceive it as environmentally beneficial. Regarding low-carbon building materials, 60% expressed willingness to pay premium prices, and 65% recognized their positive environmental impact. The CNN model demonstrated high prediction accuracy on both training and validation datasets, effectively aiding in the identification of low-carbon materials and reducing building energy consumption and carbon emissions.

Discussion: The findings highlight significant public awareness and diverse attitudes toward these critical domains, suggesting the need for improved communication and advocacy for AI's environmental benefits. The application of CNN models in the construction industry showcases a promising pathway to enhance material selection efficiency and foster sustainable practices. These insights are essential for aligning public understanding with technological advancements to achieve environmental and public health goals.

KEYWORDS

green benefits, smart city, artificial intelligence medical care, low-carbon building materials, convolutional neural network

1 Introduction

As science and technology march forward, the concept of smart cities has emerged as a beacon of innovative urban development. Through the strategic utilization of information technology and data analysis, smart cities have transformed into bustling hubs of efficiency, convenience, and comfort, ultimately enhancing the quality of life for residents (1–3). Within the framework of smart city initiatives, the integration of artificial intelligence (AI) technology and the promotion of eco-friendly building materials emerge as pivotal strategies in fostering urban sustainability and environmental stewardship. As the pace of urbanization accelerates, cities grapple with a myriad of challenges ranging from traffic congestion to environmental degradation, necessitating proactive solutions. Enter smart cities, poised to confront these challenges head-on by leveraging cutting-edge technologies such as AI, communication networks, and big data analytics to intelligently manage and optimize various urban facets, including infrastructure, services, and resource allocation. This holistic approach not only presents innovative solutions but also charts a promising path toward mitigating pressing urban concerns, paving the way for a greener, more sustainable future (4–8).

As AI technology rapidly evolves, its integration into the medical field has matured significantly. AI now plays a pivotal role in aiding physicians across various aspects of medical care, from disease diagnosis to treatment planning and prognostication, thanks to its ability to analyze vast amounts of data and deploy sophisticated machine learning algorithms (7, 9). Particularly in medical imaging, AI has achieved diagnostic accuracy comparable to seasoned medical professionals and, in some cases, even surpasses human performance. Moreover, AI facilitates personalized medical care by enabling intelligent medical devices and health management systems, enhancing both the quality and efficiency of medical services for patients. This synergy between AI and medicine heralds a new era of precision medical care, where technology empowers clinicians to deliver more accurate diagnoses and tailored treatment plans, ultimately improving patient outcomes and revolutionizing the practice of medicine (9). The extensive application of AI in the medical field, such as in diagnostics and treatment planning, has indeed enhanced efficiency and accuracy. However, it may also lead to a series of issues, including but not limited to data privacy breaches, misdiagnoses due to algorithmic bias, and the potential replacement of human physicians, which could exacerbate social inequality (10, 11). Particularly, if access to and utilization of AI technologies are uneven, it may intensify the unequal distribution of healthcare resources, thereby affecting the accessibility and equity of public health services. While AI technologies have brought numerous conveniences and efficiency improvements in the short term, their long-term impacts on social structures and the environment cannot be overlooked. Specifically, the rapid development and widespread application of AI technologies may accelerate resource consumption, potentially causing irreversible harm to the environment in the absence of appropriate green technologies and policy guidance.

The greening of AI represents a direction worthy of in-depth exploration. By optimizing algorithm designs, utilizing renewable energy-powered data centers, and developing more environmentally friendly hardware materials, it is possible to significantly reduce the carbon footprint of AI technologies (12). Additionally, promoting the application of AI in environmental protection, resource management, and sustainable development—such as through smart pollution monitoring and optimized energy distribution—represents important

pathways toward achieving greener AI. The construction industry plays a pivotal role in global energy consumption and carbon emissions, making the adoption of low-carbon building materials imperative for sustainable development. By advocating for these materials, the industry can significantly reduce its environmental impact. Low-carbon building materials offer a practical solution by decreasing building energy usage and greenhouse gas emissions. Through initiatives such as integrating renewable energy sources and utilizing efficient insulation materials, buildings can substantially decrease their reliance on fossil fuels, leading to a noticeable reduction in carbon emissions. This proactive approach addresses environmental concerns and sets the stage for a more sustainable and resilient built environment.

This study aims to explore public perceptions of the application of CNN models in the identification of low-carbon materials and how these perceptions influence the promotion and utilization of such materials. Although some research has addressed the application of AI technologies in environmental protection, studies focusing on public views of these innovative technologies and their impacts remain relatively scarce. Therefore, this research seeks to fill this gap, providing valuable insights for policymakers, businesses, and various sectors of society.

Public perceptions of these innovations are critical because they directly affect the acceptance and scope of technology application. Only when the public has a comprehensive understanding and trust in the accuracy and reliability of CNN models for low-carbon material identification can these technologies be applied in broader contexts. Furthermore, public attitudes directly influence the formulation and implementation of relevant policies, as well as corporate decisions regarding technology development and market promotion. In addition to environmental impacts, these technologies are closely related to public health. The use of low-carbon materials can reduce energy consumption and carbon emissions in buildings, thereby improving indoor air quality and decreasing the incidence of health issues such as respiratory diseases. Concurrently, the application of CNN models in medical image recognition has also achieved significant results, providing robust support for the early detection and treatment of diseases. Thus, exploring how these technologies intersect with public health not only enhances their relevance but also offers insights for broader application scenarios.

In light of the evolving landscape of smart cities, AI medical care, and low-carbon building materials, this study undertakes an exploration of their integration to bolster environmental sustainability within urban settings. The research endeavors to delve into the intersection of AI medical care and low-carbon building materials within smart city frameworks, aiming to fulfill several key objectives. Firstly, it seeks to conduct an in-depth analysis of the current applications and emerging trends of AI medical care and low-carbon building materials within the context of smart cities. Secondly, the study aims to scrutinize integration methods and mechanisms for seamlessly incorporating AI medical care and low-carbon building materials into the fabric of smart urban environments. Lastly, it endeavors to propose tangible strategies and actionable pathways for fostering synergy between AI medical care and low-carbon building materials within the context of smart cities. Through the execution of these objectives, the study introduces novel concepts and methodologies for smart city development and advocates for the wider adoption and advancement of AI medical care and low-carbon building materials. Thus, it makes significant strides toward the sustainable evolution of urban landscapes.

2 Literature review

The emergence of smart cities as a leading trend in global sustainable urban development underscores the profound impact of technological innovation on urban landscapes. As AI technology rapidly evolves, smart cities continually seek ways to harness its potential to optimize operations and enhance residents' well-being. In tandem, the exploration and implementation of low-carbon building materials have become pivotal in shaping the infrastructural fabric of these forward-thinking cities (13). This section embarks on a comprehensive review of relevant literature spanning smart cities, AI medical care, and low-carbon building materials, laying the theoretical groundwork for the framework and objectives of this study. Smart cities epitomize a paradigm shift in urban development, leveraging cutting-edge information and communication technology alongside robust data analytics to efficiently manage resources and deliver essential services across various domains such as urban planning, transportation, environmental conservation, and energy management. Muzaz et al. (14) highlight key attributes including intelligent transportation systems, energy management, and environmental monitoring as integral components of smart cities. Ultimately, the overarching objective of smart city initiatives is to enhance operational efficiency, optimize resource utilization, and ultimately improve the overall quality of life for residents. Through a synthesis of these interdisciplinary domains, this study aims to propel the advancement of smart cities toward greater sustainability and resilience in the face of urban challenges.

The integration of AI into the medical field has led to transformative breakthroughs. Research by Uthair Niu, Kaplanoglu (6) illustrates how AI empowers physicians by aiding in disease diagnosis, treatment planning, and predicting disease progression through the analysis of vast datasets and sophisticated machine learning algorithms. Moreover, Agarwal, Yadav (7) highlight the remarkable diagnostic accuracy achieved by AI-based medical care, particularly in areas like skin cancer detection and breast cancer screening, rivaling that of expert physicians. This rapid progression of AI in medical care holds immense promise for improving the precision and efficiency of medical diagnosis, reducing wastage of medical resources, and delivering superior medical care services to patients. As AI continues to evolve, its integration into medical practice stands to revolutionize patient care and enhance outcomes across diverse medical disciplines.

Low-carbon building materials play a pivotal role in mitigating greenhouse gas emissions and reducing resource consumption across their entire life cycle. Marx et al. (15) underscore the importance of investigating and adopting such materials, emphasizing their potential to significantly decrease the construction industry's energy dependency and mitigate carbon emissions from buildings. Building upon this, Nozouri et al. (16) highlight how the integration of low-carbon materials can effectively curb carbon emissions by lowering buildings' energy consumption, especially through the incorporation of renewable energy sources and the utilization of high-efficiency insulation materials. The research and implementation effort not only contribute to the creation of energy-efficient and environmentally friendly urban environments but also drive sustainable urban development. By embracing low-carbon building materials, cities can reduce their ecological footprint and move toward a more sustainable future.

In regions such as the United States and Europe, the application of AI technology in the identification of low-carbon materials has also

garnered widespread attention. These studies exhibit both similarities and differences in terms of algorithm optimization, dataset construction, and practical application scenarios when compared to research conducted in China. Comparative analysis reveals that research in different regions displays distinct characteristics and trends influenced by various factors, including cultural background, economic level, and policy environment. These differences provide a richer comparative perspective, facilitating a deeper understanding of the practical applications and potential challenges of AI technology in the identification of low-carbon materials.

In conclusion, the development of smart cities, AI medical care, and low-carbon building materials are pivotal considerations in contemporary urban sustainable development. The establishment of smart cities necessitates the incorporation of advanced technologies to elevate the management and service standards of urban areas. Meanwhile, the progression of AI medical care holds promise for enhancing the caliber and efficacy of medical services. Additionally, the adoption of low-carbon building materials emerges as a fundamental strategy for constructing energy-efficient and environmentally conscious cities. This study endeavors to investigate the integration of AI medical care and low-carbon building materials to bolster the environmental advantages of smart cities and contribute to the enduring sustainability of urban environments.

3 Methods

3.1 AI medical care in smart cities

The integration of AI into medical care within the smart city context heralds a new era of transformative benefits and possibilities. At its core, the synergy between AI and smart city infrastructure establishes a solid foundation for revolutionizing medical care delivery. The advanced intelligence and digitalization inherent in smart city infrastructure provide a fertile ground for AI applications in medical care. Medical care facilities within smart cities can capitalize on this robust technical framework to harness intelligent medical devices and systems, enabling seamless real-time collection, transmission, and analysis of medical data. This capability not only streamlines medical processes but also enhances the efficiency and effectiveness of medical care services. For instance, through continuous patient monitoring facilitated by intelligent devices, physicians gain unprecedented insights into patients' physiological parameters, enabling remote diagnosis, prompt treatment adjustments, and ultimately, improved treatment outcomes. Furthermore, AI technology offers unparalleled advantages in medical imaging diagnosis, disease prediction, and diagnosis. Within the smart city ecosystem, medical care institutions can leverage sophisticated machine learning algorithms and big data analytics to glean invaluable insights from vast medical datasets. By doing so, they can refine the accuracy and precision of medical diagnosis to unprecedented levels. For example, AI-powered medical imaging diagnosis systems equipped with deep learning algorithms can automatically analyze medical images, aiding physicians in rapid disease identification, minimizing diagnostic errors, and elevating diagnostic accuracy to new heights. Moreover, AI medical care in smart cities paves the way for personalized diagnosis and treatment strategies tailored to individual patient needs. By leveraging patients' medical histories, genetic profiles, and lifestyle data, medical care institutions can harness AI algorithms to anticipate health risks and

derive personalized preventive and treatment measures. This approach embodies the concept of precision medicine, wherein medical care interventions are finely tailored to each patient's unique characteristics and circumstances (17, 18).

The integration of AI into medical care within the framework of smart city infrastructure represents a paradigm shift in medical care delivery, offering multifaceted benefits and transformative potential. At its core, the augmentation of intelligence and digitalization within smart city infrastructure establishes a robust technical environment conducive to the seamless collection, transmission, processing, and application of AI-driven medical services. This convergence unlocks a myriad of opportunities for intelligent, personalized, and precise medical care delivery, reshaping the landscape of medical care provision. Firstly, smart city infrastructure serves as a catalyst for seamless data collection and transmission, laying the groundwork for real-time monitoring and data acquisition. The heightened intelligence embedded in smart medical devices and sensors enables the continuous gathering of patients' physiological parameters, condition data, and medical images. Leveraging the network infrastructure of smart cities, this wealth of data can be swiftly transmitted and stored, facilitating personalized medical services and furnishing invaluable insights for optimization and precision in medical care delivery. Secondly, the robust data processing and analysis capabilities afforded by smart city infrastructure empower medical care institutions to delve into vast medical datasets with unprecedented depth and efficiency. Through the utilization of information systems and big data platforms, medical care providers can harness formidable computing and storage capacities to process and analyze complex medical data. Cloud computing and big data technologies enable the exploration of patients' health statuses and disease progression patterns, equipping physicians with enhanced diagnostic and treatment capabilities grounded in empirical evidence and scientific rigor. Furthermore, the intelligence and digitalization of smart city infrastructure enable the delivery of personalized medical services tailored to individual patient needs. By leveraging AI technologies and big data platforms, medical care facilities can scrutinize patients' medical histories, genetic profiles, and lifestyle data to extract actionable insights. This facilitates the provision of tailored diagnosis and treatment plans, as well as personalized health management recommendations, thereby enhancing the precision and customization of medical services to unprecedented levels. In addition, smart city infrastructure supports the optimal allocation of medical resources, promoting the efficient utilization of medical care resources. By leveraging AI capabilities and big data analytics, medical institutions can analyze and forecast the supply and demand dynamics of medical resources. This enables the rational allocation of medical care resources, optimization of service layouts, and enhancement of service quality and efficiency, ultimately leading to improved patient outcomes and satisfaction. Lastly, the robust information security systems embedded within smart city infrastructure ensure the confidentiality and integrity of medical data. Privacy protection mechanisms safeguard against unauthorized access and misuse of medical information, preserving patients' rights, interests, and privacy. This instills confidence among patients and medical care providers alike, fostering a secure environment for the exchange of sensitive medical information. In conclusion, the evolution of smart city infrastructure plays a pivotal role in advancing the integration of AI into medical care, ushering in a new era of

intelligent and data-driven medical care delivery. By leveraging the capabilities of smart city infrastructure, medical care institutions can unlock unprecedented opportunities for personalized, precise, and efficient medical care provision, ultimately improving patient outcomes and shaping the future of medical care delivery (19–21).

The use of low-carbon building materials can significantly reduce carbon emissions during the operational phase of buildings, thereby improving urban air quality and decreasing health issues related to respiratory diseases caused by air pollution. Concurrently, the application of AI in healthcare, such as predicting disease risk through big data analysis and optimizing medical resource allocation, can further enhance public health and collectively promote the development of healthy cities alongside low-carbon materials. By collecting and analyzing vast amounts of environmental, health, and socioeconomic data, AI can construct complex models to predict changes in human health risks under various carbon emission scenarios. This analytical capability assists policymakers in accurately identifying high-risk areas and populations, enabling the formulation of effective emission reduction measures and health intervention strategies.

3.2 Application of low-carbon building materials in smart cities

Low-carbon building materials play a critical role in advancing sustainable construction practices, particularly within the context of smart cities. These materials encompass a diverse range of building elements meticulously engineered to minimize environmental impact and reduce greenhouse gas emissions throughout their entire life cycle, from production to disposal (22). With mounting concerns surrounding climate change, the adoption of low-carbon building materials has emerged as a pivotal trend within the construction industry. At its core, the adoption of such materials aligns with the overarching goal of decarbonization, seeking to address construction needs while mitigating the environmental footprint associated with building activities. This necessitates a multifaceted approach that encompasses various strategies, including the utilization of renewable resources, optimization of energy consumption, and reduction of emissions during manufacturing processes. For instance, substituting traditional building materials with recycled alternatives, implementing energy-efficient production techniques, and optimizing transportation methods for materials are all effective measures aimed at achieving low-carbon objectives (23). Table 1 (24) provides an overview of the key characteristics defining low-carbon building materials, illustrating their importance in fostering sustainable development within smart city environments.

The utilization of low-carbon building materials has profoundly influenced the urban environment and residents' health in a multitude of ways, shaping a more sustainable and livable future for urban dwellers. Firstly, these materials play a pivotal role in improving air quality within urban areas. Crafted from eco-friendly components like natural fibers and recycled materials, low-carbon building materials minimize the emission of harmful substances, thereby ameliorating urban air quality. Compared to conventional building materials, these eco-friendly alternatives generate fewer pollutants during production and are more conducive to recycling post-use, alleviating environmental strain and reducing air pollution.

TABLE 1 Concepts and characteristics of low-carbon building materials.

Characteristics	Description
Green and environmental-friendly	Low-carbon building materials typically originate from sustainable resources or possess recyclable properties, such as bamboo and recycled steel. They exhibit minimal environmental impact during production and use, thereby reducing the consumption of natural resources and mitigating environmental damage.
Energy efficiency	Low-carbon building materials demonstrate excellent energy utilization efficiency, thereby reducing energy consumption during the operational phase of buildings. For instance, thermal insulation materials with superior insulation properties contribute to the reduction of heating and cooling energy consumption in buildings.
Low-carbon emission	Low-carbon building materials prioritize the adoption of low-energy and low-emission production processes, often leveraging low-carbon fuels and energy sources. These practices effectively mitigate the release of harmful emissions, including greenhouse gases, during the manufacturing process.
Recyclability	The design of low-carbon building materials emphasizes sustainability across the entire lifecycle, with a focus on material reuse and recycling. By facilitating material disassembly and recycling, these materials achieve recyclability, thereby reducing resource consumption and minimizing waste generation.

levels. Consequently, the health of urban inhabitants is enhanced as they breathe cleaner air, reducing the risk of respiratory illnesses and improving overall well-being. Secondly, the adoption of low-carbon building materials contributes to enhancing indoor environmental quality. These materials typically boast superior environmental adaptability and comfort attributes, such as effective thermal insulation, sound absorption, and moisture regulation capabilities. By improving indoor air quality and comfort, low-carbon building materials mitigate indoor air pollution and odors, creating healthier living environments for residents (23, 24). For instance, incorporating paints and construction materials with low volatile organic compound (VOC) levels diminishes the presence of hazardous substances in indoor air, reducing the risk of respiratory issues and enhancing overall health. Furthermore, the integration of low-carbon building materials aids in mitigating the urban heat island effect, a phenomenon where urban areas experience elevated temperatures compared to surrounding rural areas. Traditional materials like concrete and steel possess high heat capacity and thermal conductivity, exacerbating the urban heat island effect by absorbing and retaining solar energy. However, materials with low heat capacity and high reflectivity, such as reflective roofs and green roofs, effectively attenuate building and city temperature rises, ameliorating urban climates and bolstering residents' living comfort. Additionally, the use of lightweight and recycled materials in construction reduces buildings' structural weight, subsequently curbing their energy consumption and carbon emissions. By adhering to low-carbon building design principles, such as optimizing natural light utilization and promoting natural ventilation, buildings can further diminish their energy usage and dependence on external resources. This not only reduces greenhouse gas emissions but also promotes sustainable urban development by conserving energy and fostering resilience to climate change. Lastly, the integration of low-carbon building materials contributes to enhancing community health and residents' well-being. By bolstering air quality, indoor environments, and urban climates, these materials mitigate the adverse impacts of environmental pollution and climate change on residents' health, fostering community cohesion and enhancing overall quality of life. In essence, the utilization of low-carbon building materials represents a critical step toward creating healthier, more sustainable urban environments for present and future generations (25).

3.3 Integration of AI medical care and low-carbon building materials in smart cities

This study harnesses the power of AI and convolutional neural network (CNN) technology to revolutionize the production and design optimization of building materials. By constructing a sophisticated neural network model, the intricate correlations between building material performance and structure can be unraveled, drawing insights from extensive experimental datasets. This enables precise predictions of material performance under diverse design scenarios. For example, employing deep learning techniques facilitates the optimization of building material microstructures, ensuring the attainment of optimal mechanical properties and durability for enhanced structural integrity and longevity.

In the realm of deep learning, CNNs stand out as powerful tools for processing and analyzing grid-structured data tasks, particularly images and videos. Inspired by the human visual system, CNNs excel at extracting features from input data through layers of convolution and pooling operations, ultimately performing tasks such as classification or regression through fully connected layers. The relevance of CNNs to low-carbon building materials lies in their potential to revolutionize architectural design and material selection processes, paving the way for more environmentally friendly and sustainable construction practices. CNNs play a crucial role in analyzing the characteristics and performance of building materials. By inputting images of various materials into CNN models, their physical properties, structures, and textures can be classified and predicted with remarkable accuracy. This empowers designers and engineers to make informed decisions when selecting low-carbon building materials that meet specific requirements, thereby promoting sustainable building practices. Furthermore, CNNs contribute to optimizing the energy efficiency of buildings. By analyzing architectural appearance, layout, and material properties, CNNs can forecast building energy consumption and provide optimization recommendations. Adjusting window positioning and size, as well as modifying material thermal conductivity, based on CNN insights can significantly reduce energy consumption and minimize environmental impact. Moreover, CNNs are instrumental in the research and innovation of building materials. By analyzing existing materials' characteristics and integrating extensive data and simulation

experiments. CNNs aid scientists and engineers in developing novel low-carbon building materials. These materials may possess enhanced insulation properties, durability, and recyclability, thereby advancing the construction industry toward greater sustainability and eco-consciousness. In conclusion, CNNs offer immense potential in the exploration and implementation of low-carbon building materials. Leveraging CNN technology enables a deeper understanding and optimization of building material performance, enhances building energy efficiency, and propels the construction sector toward a more sustainable trajectory. This methodology aligns with global efforts to mitigate climate change and promote environmental conservation.

A CNN model is constructed to process the structural and performance data of materials, followed by obtaining the optimal design solution through model prediction and optimization. The model's process flow is illustrated in Figure 1.

The specific steps are as follows:

- (1) Data collection and preprocessing: structural and performance data of building materials, including material composition, physical properties, mechanical performance, etc., were gathered. The collected data underwent preprocessing, including tasks such as data cleaning and normalization, to facilitate the training and optimization of the neural network.
- (2) Establishing the CNN model: the input of the neural network can consist of structural feature data of materials, such as crystal structure, element distribution, etc., while the output can be the predicted performance of materials, such as strength, thermal conductivity, etc. The model is constructed using convolutional layers, pooling layers, and fully connected layers. The output of the convolutional layer is calculated via Equation 1:

$$z_{ij}^l = \sum_{m=1}^{r-1} \sum_{n=1}^{s-1} W_{mn}^l \cdot x_{i-m, j-n}^{l-1} + b_j^l \quad (1)$$

In Equation 1, z_{ij}^l represents the weighted sum of neurons in the i -th row and j -th column of the l -th layer. W_{mn}^l is the weight of the convolution kernel, $x_{i-m, j-n}^{l-1}$ is the input data of the $(l-1)$ -th layer, and b_j^l signifies the bias term.

The Rectified Linear Unit (ReLU) activation function is defined as Equation 2:

$$a_j^l = \text{ReLU}(z_j^l) \quad (2)$$

In Equation 2, a_j^l represents the output of the neuron after the activation function, and ReLU denotes a commonly used activation function defined as $\text{ReLU}(x) = \max(0, x)$.

The output of the pooling layer is calculated using Equation 3:

$$p_j^l = \text{pool}(a_j^l) \quad (3)$$

In Equation 3, p_j^l represents the output of the pooling layer, and pool is the pooling function, such as Max Pooling or Average Pooling.

The output of the fully connected layer is calculated using Equations 4 and 5 below:



FIGURE 1
Process flow of the CNN model.

$$z_j^l = \sum_{i=1}^{n-1} W_{ij}^l \cdot a_i^{l-1} + b_j^l \quad (4)$$

$$a_j^l = \text{ReLU}(z_j^l) \quad (5)$$

Here, z_j^l represents the weighted sum of the j -th neuron of the output layer, W_{ij}^l refers to the weight connected to the output layer, a_i^{l-1} signifies the output of the i -th neuron of the output layer, and b_j^l denotes the bias term of the output layer.

- (3) Model training and optimization: training the neural network model involves utilizing collected data to learn the intricate relationship between material structure and performance. This process employs optimization algorithms, such as gradient descent algorithms, to refine model parameters. Through iterative adjustments, these algorithms minimize prediction errors and enhance the overall accuracy of the model, ensuring that it effectively captures the underlying patterns within the data.
- (4) Model verification and evaluation: following model training, an independent test dataset is employed to verify and evaluate the trained model. This step assesses the model's generalization capability and prediction accuracy. Based on validation results, the model undergoes adjustments and enhancements to further improve its performance and reliability, ensuring its effectiveness in real-world applications.
- (5) Optimized design plan generation: the trained neural network model, now refined and validated, is deployed to predict and optimize building material structure and performance. By adjusting input parameters based on specific design

requirements and objectives, the model generates an optimal design solution tailored to the project's needs. This process ensures that the resulting design plan maximizes performance while adhering to predefined constraints and goals.

- (6) **Plan verification and experimentation:** the generated optimized design plan is translated into tangible building materials, and experimental verification ensues. Through rigorous testing and experimentation, the performance of the design plan is evaluated, and feedback from experimental outcomes is used to further refine and optimize the design. This iterative process establishes a closed-loop optimization cycle, continuously improving the design plan based on real-world feedback and ensuring its effectiveness in practice.

During the training of the CNN model, the following parameter settings are employed: the learning rate is set to 0.001 to control the model's update speed during training, the batch size is set to 32, in each convolutional layer, the kernel size is 3×3 , and the ReLU activation function is applied following the convolutional and fully connected layers to enhance the model's nonlinear capacity.

For each type of building material, 80 samples are prepared, resulting in a total of 90 samples across three material types. Each sample includes 16 features, such as the composition ratio, manufacturing process parameters, and physical property indicators. The range for compressive strength testing is set at 20–100 MPa.

In the test set, the mean squared error (MSE) for the model's compressive strength predictions is 2.5 MPa, while the MSE for flexural strength predictions is 1.2 MPa. In field tests, the error between the model's predictions and the actual values falls within an acceptable range, indicating that the model exhibits strong predictive capabilities and practicality.

3.4 Questionnaire survey and parameter settings

3.4.1 Questionnaire survey

This study utilizes a cross-sectional research design aimed at investigating public perceptions and attitudes toward smart cities, AI in healthcare, and low-carbon building materials at the current time point. Data are collected from 200 randomly selected respondents regarding their awareness, acceptance, and expectations in these areas. This design facilitates the acquisition of a snapshot of current public opinions, providing crucial insights into the image and status of these domains in the public mind. The survey is conducted from April 2022 to October 2022, spanning a duration of 6 months. Following the elimination of incomplete responses, 190 valid questionnaires are obtained, resulting in an impressive response rate of 95%. This high response rate ensures the reliability and validity of the survey findings. The questionnaire primarily includes sections on personal information, understanding and attitudes toward smart cities, knowledge and attitudes regarding AI in healthcare, attitudes and purchasing intentions toward low-carbon building materials, and satisfaction with proposed improvements in the survey materials. A random sampling method is employed to ensure that the sample adequately represents individuals of varying ages, genders, professions, and income levels. This approach aims to gather the broadest and most diverse public opinions possible.

In exploring perceptions of AI, a series of questions is designed to gain a deeper understanding of the public's attitudes toward its applications in daily life. This includes inquiries about the perceived value of AI, concerns regarding potential risks, and views on its impact on employment. These questions aim to reveal the diverse perspectives held by the public regarding AI technology, ranging from enthusiastic support to reservations, and even concerns and opposition. For perceptions of smart cities, a set of questions is developed to assess the public's understanding of the concept of smart cities and their views on the environmental impact of such initiatives. Special attention is given to identifying areas in which the public believes improvements are needed in the construction of smart cities, with the intent of guiding future policy development and practical implementation. Regarding views on low-carbon materials, the questions primarily focus on the public's understanding of the concept and significance of low-carbon materials, their awareness of the environmental implications, and their willingness to choose low-carbon materials in everyday life, as well as the influencing factors. Additionally, the questionnaire includes several questions related to income level, such as annual household income and stability, in order to indirectly assess the impact of economic status on perceptions and attitudes in these areas.

3.4.2 Neural network parameter settings

In the training phase, a dataset comprising 1,000 sample data points is utilized, while an additional 200 sample data points are reserved for validation purposes. The learning rate employed during training is set at 0.01, ensuring a balanced approach to gradient descent optimization. The training cycle spanned 100 epochs, allowing the neural network model to iteratively learn and adapt to the underlying patterns in the data, ultimately enhancing its predictive capabilities and performance.

3.5 Ethic approval

The experiment was approved by Academic Ethics Review Committee of Guangzhou University (No. GZHT2024109), China, on March 23, 2024. Our study did not involve animal or human clinical trials and was not unethical. In accordance with the ethical principles outlined in the Declaration of Helsinki, all participants provided informed consent before participating in the study. The anonymity and confidentiality of the participant guaranteed, and participation was completely voluntary. Participants volunteered to take part in the interview. Prior to participating in the interview, they were informed of the purpose of the study and were told that "submission of records" was considered informed consent. Participants could withdraw at any time during the participation process.

4 Results

4.1 Descriptive statistics

4.1.1 Personal information of the survey subjects

The demographic data collected from the survey participants is summarized in [Figure 1](#).

As depicted in Figure 2, males constitute 60% of the survey respondents, while females make up 40%. The age distribution is predominantly concentrated between 31 and 60 years old. These findings indicate a relatively balanced gender ratio among participants, with the majority falling within the middle-aged demographic. This demographic profile enables a more nuanced understanding of attitudes and perspectives regarding smart cities, AI medical care, and low-carbon building materials across different demographic groups.

4.1.2 Smart city statistics

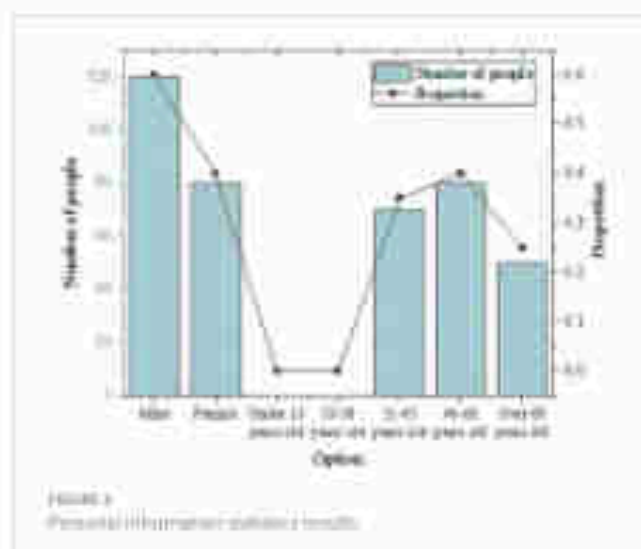
The statistical findings regarding smart cities are presented in Figure 3.

As illustrated in Figure 3, 80% of the respondents possess an understanding of smart cities, with 30% indicating a high level of comprehension. Additionally, 60% of the participants perceive smart cities to have a positive impact on the environment. These results suggest that a considerable majority of the respondents exhibit a certain level of familiarity with smart city concepts, and a notable portion acknowledges their beneficial influence on environmental conservation and sustainable living. This trend likely signifies an increasing awareness of sustainable development and environmental stewardship, as well as a favorable disposition toward the advancement of smart city initiatives. Such insights hold significant implications for guiding future urban planning and developmental endeavors.

4.1.3 AI medical statistics

The statistical findings regarding AI medical treatment are presented in Figure 4.

As depicted in Figure 4, 70% of the respondents exhibit an understanding of the application of AI in the medical field, with 45% expressing belief in its positive impact. Through optimizing supply chain management, enhancing energy efficiency, and promoting the rational allocation of medical resources, AI contributes to reducing the negative environmental impact of healthcare. Proponents also emphasize that AI can drive innovation in medical technology, leading to the development of more environmentally friendly and efficient medical devices and treatment methods. These innovations not only improve the quality of healthcare services but also mitigate environmental damage. This indicates a substantial level of comprehension among participants regarding the integration of AI in medical care, with a notable portion acknowledging its potential environmental benefits. However, 30% of respondents remain unfamiliar with this domain, and 55% perceive its impact as unfavorable, possibly reflecting apprehensions and uncertainties surrounding the adoption of novel technologies. Some skeptics argue that while AI can enhance the efficiency of healthcare services, the computational resources and energy consumption required for its operation are substantial. If these resources are not managed and utilized effectively, they may pose adverse environmental impacts. This skepticism primarily stems from several factors: first, the public's limited understanding of AI technology results in insufficient awareness of its potential environmental implications; second, there is significant concern regarding privacy and security issues in the healthcare sector, with fears that the introduction of AI technology may introduce new risks; third, varying levels of acceptance of low-carbon and environmentally friendly concepts among the public lead to differences in expectations and attitudes toward the application of AI in healthcare. These findings underscore the necessity for



enhanced dissemination and advocacy of AI in medical care. Moreover, it underscores the importance of gauging public perception and attitudes toward its prospective environmental implications.

4.1.4 Statistics of low-carbon building materials

The statistical analysis of low-carbon building materials is illustrated in Figure 5.

As depicted in Figure 5, 80% of respondents have expressed their willingness to pay higher prices for purchasing low-carbon building materials, indicating a notable level of recognition of this material type. Furthermore, 30% of respondents possess a substantial understanding or extensive knowledge regarding low-carbon building materials. However, 35% of respondents exhibit limited knowledge, signifying the necessity for further publicity and dissemination efforts. Regarding their recognition of environmental impact, 65% of respondents concur that low-carbon building materials can have a positive influence. These findings suggest that while there exists a certain level of awareness regarding low-carbon building materials, concerted efforts to enhance public awareness and underscore their environmental benefits are imperative to foster widespread acceptance and recognition of their adoption.

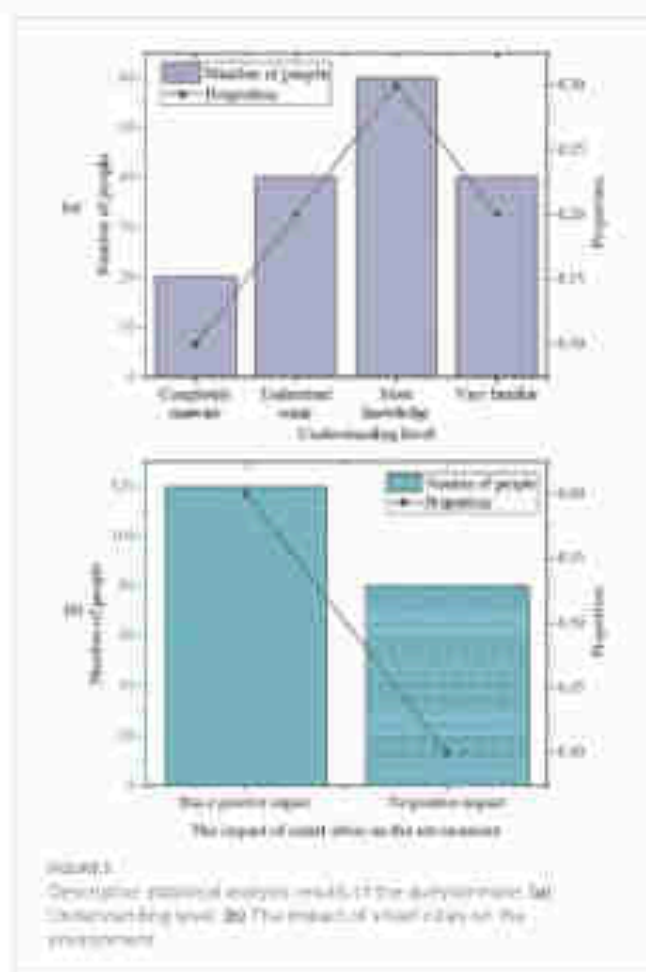
4.1.5 Satisfaction survey

The satisfaction level regarding material improvements was analyzed, and the results are presented in Figure 6.

As depicted in Figure 6, 40% of participants expressed satisfaction, while 25% reported being very satisfied. Additionally, 20% exhibited a neutral attitude, while the proportions of dissatisfaction and extreme dissatisfaction were 10 and 5%, respectively. Overall, a majority of participants expressed satisfaction or high satisfaction levels with the survey. This indicates a notable level of recognition for the survey content, as well as the information or services provided throughout the survey process.

4.2 Neural network model performance analysis

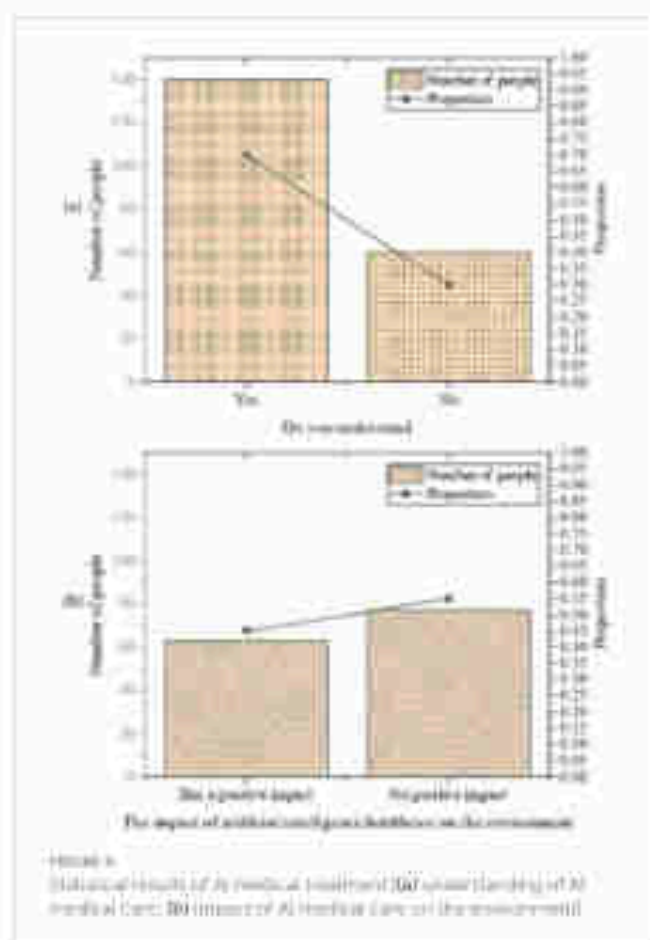
The CNN model constructed was trained and verified, yielding the following results, as depicted in Figure 7.



As depicted in Figure 7, the model showcases exceptional performance on the training set, boasting remarkably high precision, recall, and $F1$ scores. Despite a slight decline in performance observed on the validation set, the model exhibits commendable generalization capabilities, with accuracy and recall rates consistently exceeding 95%. Notably, the MSE of the model remains remarkably low, indicating minimal disparity between predicted and actual values. Specifically, the MSE on the training set is a mere 0.001, indicative of a robust fit to the training data. Even with a slightly higher MSE observed on the validation set (0.002), the model maintains strong performance, highlighting its capacity to predict new data with precision and reliability. This result is consistent with the findings of Guan and Wang (2024). These results underscore the effectiveness and reliability of the model in handling unseen data and generalizing well beyond the training set.

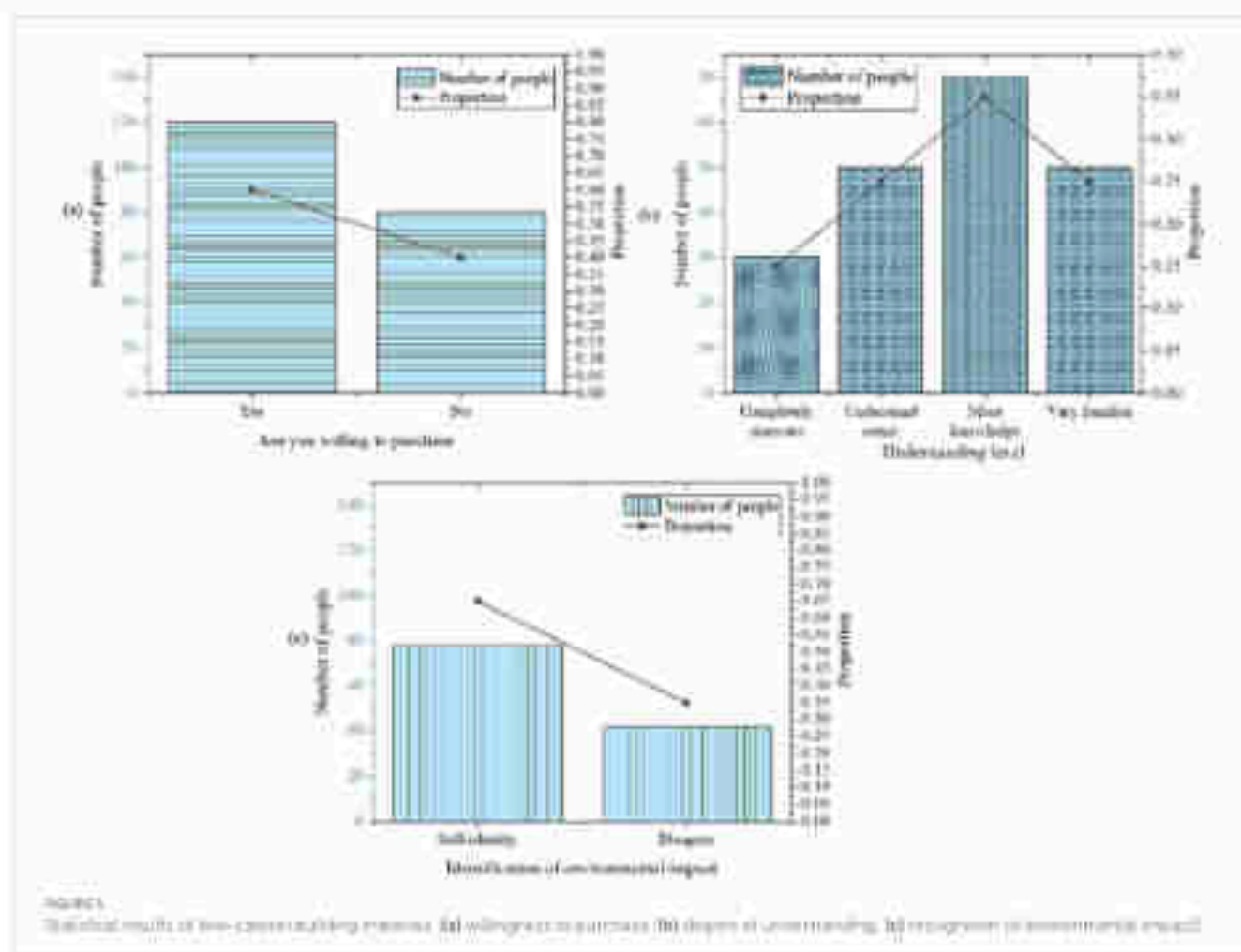
5 Discussion

In cultures that emphasize collectivism and obedience to authority, individuals may be more inclined to accept decisions made by AI, whereas cultures that prioritize individualism and free will may exhibit greater vigilance regarding the potential threats that AI poses to individual rights. Environmental awareness varies across different cultural contexts. In cultures with a strong emphasis on environmental protection, individuals may be more concerned about the potential



impacts of new technologies, such as AI, on the environment and are more likely to support technological applications that contribute to environmental conservation. In Europe, the application of AI places a significant focus on privacy protection and ethical standards, underscoring the importance of sustainable development and social responsibility in AI technology. Germany has made remarkable progress in intelligent manufacturing and Industry 4.0 while actively promoting the application of AI in fields such as healthcare and education. In Asia, particularly in China, Japan, and South Korea, there has been rapid development in the application of AI technologies. These countries have achieved significant breakthroughs in areas such as smart cities, smart homes, and smart finance, particularly benefiting from their advantages in big data processing, cloud computing, and Internet of Things technologies. Denmark is recognized as one of the leading countries in global wind energy production, achieving a green transformation of its energy structure and low-carbon development through the large-scale utilization of renewable energy sources like wind. Denmark's wind energy projects serve as successful models for the global adoption of low-carbon energy.

In the field of intelligent transportation, the application of AI significantly enhances the efficiency and safety of urban traffic systems. By integrating big data analytics and machine learning algorithms, AI can predict traffic flow in real time, optimize traffic signal control, reduce congestion, and assist in planning more efficient public transportation routes. Furthermore, the continuous development of autonomous driving technology, which relies on AI



decision-making systems, is expected to greatly improve road safety and decrease traffic accidents. When combined with IoT technologies, AI can enable intelligent connectivity between vehicles and infrastructure, further enhancing the overall effectiveness of transportation systems.

In energy management, the application of AI contributes to the development of greener and more efficient energy systems within smart cities. Utilizing deep learning and other technologies, AI can forecast energy demand and optimize energy distribution, thereby improving energy utilization efficiency and reducing waste. Additionally, in conjunction with smart grid technology, AI can monitor and control electricity supply in real time, ensuring the stable operation of the grid and facilitating rapid energy dispatch when necessary. In the renewable energy sector, AI can also optimize the utilization of clean energy sources, such as solar and wind power, promoting the optimization and upgrading of urban energy structures. Regarding smart city governance, the application of AI offers novel perspectives and tools for urban management. Through big data analysis and natural language processing techniques, AI can collect and analyze urban operational data in real time, providing scientific support for government decision-making. AI can assist in monitoring urban environmental quality, predicting disaster risks, and optimizing the allocation of public service resources.

The return on investment for smart cities and low-carbon materials may be extended, necessitating collaborative efforts and

long-term commitments from government, enterprises, and individuals. As the advancement of intelligence and low-carbon initiatives progresses, employment opportunities in traditional industries may decline, while new job openings in emerging sectors could increase. This transition may lead to instability in employment structures and social stratification. The implementation of smart cities and low-carbon materials relies on advanced technologies and information systems, which could result in an over-reliance on technology, potentially impacting the autonomy and diversity of social life. The perspectives of policymakers are crucial in the execution of proposed strategies. Policy support and guidance can stimulate the enthusiasm of businesses and individuals, facilitating the widespread adoption of smart cities and low-carbon materials. Regulatory frameworks and oversight are essential for maintaining market order and ensuring the legal and compliant use of technology. During the implementation of smart cities and low-carbon materials, construction companies must focus on cost control and benefit assessment to ensure the economic feasibility and sustainability of projects. Although the production costs of low-carbon materials may exceed those of traditional materials, the energy savings and emissions reduction benefits, along with long-term economic returns during their use, must also be considered. Buildings constructed with low-carbon materials exhibit superior performance in insulation, thermal regulation, and lighting, leading to reduced energy consumption and operational costs. Governments should formulate both long-term and

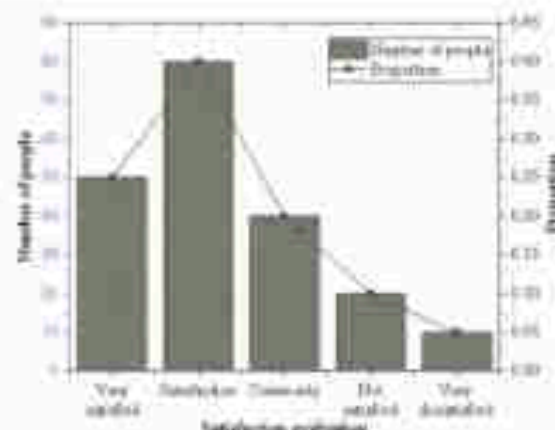


FIGURE 6
Satisfaction survey results on internet usage.

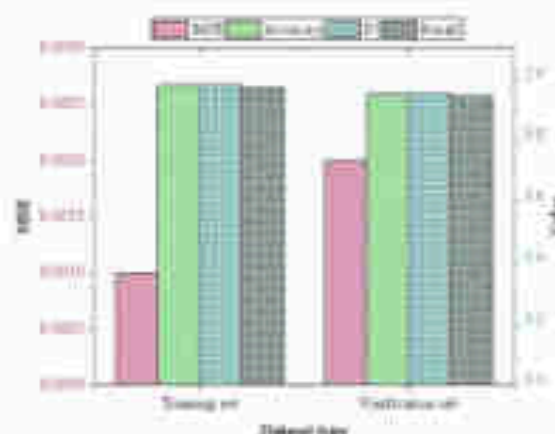


FIGURE 7
Neural network model performance results.

short-term strategic plans that clearly delineate the roles and significance of AI and low-carbon materials in economic development, environmental protection, and social progress. These strategic plans should encompass various aspects such as technology research and development, industry cultivation, policy support, and talent training to ensure coherence and systemic alignment in policy formulation.

In the field of healthcare, the application of AI often relies on extensive personal health data. However, numerous ethical challenges arise during the collection, storage, and processing of this data, particularly concerning data privacy. Personal health data is highly sensitive, and its breach can pose severe privacy risks to individuals. Malicious actors may exploit this data for fraud, identity theft, or other illicit activities. Even in cases where data is not directly disclosed to external entities, inadequate management and protection can lead to misuse within organizations. Healthcare institutions or researchers might access or utilize this data without authorization for unethical research or commercial purposes.

The training data for AI systems often originates from specific groups or environments, which may introduce bias when algorithms process data from different groups or contexts. If the training data predominantly comprises individuals of a particular race or gender,

the algorithm may exhibit biases when handling data from other races or genders. Participants may tend to overestimate their understanding of smart cities, AI, and low-carbon materials. This overestimation may stem from various factors, such as social desirability bias (where respondents feel pressured to display a higher level of understanding of emerging technologies), memory biases (where respondents may struggle to accurately recall or assess their knowledge), or cognitive biases (where respondents may hold inflated self-evaluations of their abilities or knowledge). To address this, it is essential to clearly communicate the study's objectives and significance to respondents before data collection, as well as the potential biases in self-reported data. By increasing respondents' awareness, they can be encouraged to more authentically reflect their knowledge levels, thereby minimizing instances of overestimation or underestimation.

The performance of CNN models may be influenced by factors such as dataset quality, training methodologies, and parameter settings. As the model has not been tested in real-world environments, its performance in practical applications remains uncertain. To mitigate the impact of these limitations, methodologies such as cross-validation, model tuning, and performance evaluation are employed during the research process to enhance the model's accuracy and generalization capabilities.

6 Conclusion

This study employs a multifaceted approach, combining both quantitative and computational methods, to derive into perceptions and attitudes toward key aspects of urban development: smart cities, AI medical care, and low-carbon building materials. Through a combination of questionnaire surveys and neural network modeling, this study endeavors to provide a comprehensive understanding of public sentiments and expectations in these domains. This study employs a random sampling method to ensure the diversity and representativeness of the sample. Efforts are made to include respondents from various age groups, genders, occupations, and regions to minimize the impact of self-selection bias. The survey findings reveal a generally positive outlook toward smart cities and low-carbon building materials among participants, highlighting an increasing awareness and acceptance of sustainable urban development practices. However, there exists a nuanced understanding and some skepticism regarding AI medical care, suggesting a need for further education and awareness campaigns in this area. AI is expected to facilitate the widespread adoption of personalized medical services by analyzing information related to patients' genetics, lifestyle habits, and medical histories to provide tailored treatment plans and health management recommendations. This approach is anticipated to significantly enhance the efficiency and effectiveness of healthcare services while reducing medical costs. Strengthening collaboration among academia, industry, and healthcare institutions is essential for advancing the research and application of AI technologies. By sharing resources, experiences, and knowledge, the innovation and dissemination of technology can be accelerated.

The findings of this study indicate that participants generally hold a positive attitude, suggesting an increasing awareness and acceptance of sustainable urban development practices among the public. This conclusion underscores the significant role of smart cities in promoting urban sustainability and provides robust support for

policymakers to further advance the construction and development of smart cities. In the realm of AI in healthcare, although the public possesses a certain level of understanding regarding its applications, there are nuanced perceptions and some skepticism. This reflects concerns regarding the potential risks and uncertainties associated with new technologies. Therefore, it is imperative to enhance educational and promotional activities in the future to improve public comprehension of AI in healthcare and alleviate concerns. The CNN model developed here demonstrates robust performance, exhibiting high prediction accuracy on both the training and validation sets. Despite its strengths, limitations such as a relatively small sample size and scope of survey questions, as well as the lack of verification on a larger scale, may impact the representativeness and reliability of the results. Future research endeavors could focus on expanding the sample size, refining survey question formulation, validating the model's generalization capabilities on a larger scale, and conducting more comprehensive real-world analyses and evaluations of smart city initiatives, AI medical care, and low-carbon building materials to provide actionable insights for public health and sustainable urban development. Future research will expand the sample size to encompass a broader population and geographical areas. This endeavor will facilitate a more comprehensive understanding of public perceptions and attitudes toward these domains, thereby enhancing the representativeness and applicability of the research findings.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Academic Ethics Review Committee of Guangzhou University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

References

1. Kotha, R.V., William, E., Towdler, P.M., Pathanwar, D.S., Parida, A.R. Smart city implementation based on internet of things integrated with optimization technology. *Alamida Sci.* (2022) 27:202789. doi: 10.1016/j.alamida.2022.100789
2. Ullah, A., Fird, A.M., Li, L., Hafeez, I., Rehman, A., Mahmood, T., et al. Smart Office: the role of internet of things and machine learning in creating a data-centric, smart environment. *Complex. Intell. Syst.* (2023) 10:3607–17. doi: 10.1007/s40347-023-01175-4
3. Anthony, B. Data-driven approaches for smart city planning and design: a case scenario on urban data management. *Big Data Res. Comput.* (2023) 25:221–40. doi: 10.1109/BigData.2022.10022
4. Gao, L., Baroud, G., Specking, E., Pohl, B., Buchner, R. Smart cities—a structured literature review. *Smart Cities* (2022) 6:1118–43. doi: 10.3390/smartcities6040188
5. Park, J., Wei, S. Evolution of the smart city: from extensions to governance, sustainability and smart urbanization from an ICT-based urban system. *Int. J. Urban Sci.* (2022) 27:10–28. doi: 10.1080/13600344.2022.2110143
6. Pua, Y.C., Pooja, C.H., Pughan, B.P., Barbina, C.E., Argile, A.L., & Lim, T.C. et al. Analyzing the challenges for future smart and sustainable cities. *Asian Pac. J. (2022) 15:7996*. doi: 10.3389/apj.2022.100796

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JS: Conceptualization, Methodology, Writing – review & editing, XC: Data curation, Methodology, Writing – review & editing, XY: Supervision, Writing – original draft, YG: Formal analysis, Resources, Writing – review & editing, YT: Visualization, Writing – original draft, YG: Formal analysis, Project administration, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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7. Agarwal, S., Sahai, A.S., Dinesh, V., Varma, K.S., Prakash, S.S., Jaiswal, S. By artificial intelligence algorithms and machine learning models to diagnosis cancer. *Met. Today Res.* (2022) 97:2389–71. doi: 10.1016/j.mtrp.2022.07.004

8. Shafar, M., H., Karamouzi, E., Nook, A. Performance of artificial intelligence techniques in disease diagnosis and prediction. *Diagn. Artif. Intell.* (2023) 3:1. doi: 10.1007/s44143-023-00040-1

9. Kumar, I., Kumar, R., Kumar, D. A structured analysis to study the role of machine learning and deep learning in the healthcare sector with big data analytics. *Arab. J. Comput. Method Eng.* (2023) 10:3673–731. doi: 10.1007/s11831-023-10013-9

10. Li, X., Wang, Q., Tang, Y. The impact of artificial intelligence development on urban energy efficiency—based on the perspective of Smart City policy. *Sustain. Dev.* (2024) 10:3210. doi: 10.3390/su16061210

11. HERNANDEZ-SOLÍS, C., BUSTO, J., DELGADO, J., ANDRÉS, T. How artificial intelligence takes health and sustainability on a horseman? Towards green technologies for multidimensional health and environmental justice. *Global Health* (2024) 15:1222108. doi: 10.1089/glob.1287462.2024.2322108

12. Yilmazlar, T.; Mohamed, R.; Cankaya, M. Green artificial intelligence towards an efficient, sustainable and equitable technology for smart cities and future. *Sustain. For.* **2023**, *13*, 4952. doi: 10.3390/su13104952
13. Shang, W.-L.; Liu, X. Low carbon technology for carbon neutrality in sustainable cities: a survey. *Sustain. Cities Soc.* **2023**, *92*, 104489. doi: 10.1016/j.scs.2023.104489
14. Musa, A.; Makare, S.; Akpan, O.; Ogunro, W.; Akhavan, M.; Harpaz, Y. Sustainable traffic Management for Smart Cities Using Internet-of-Things-Oriented Intelligent Transportation Systems (ITS): challenges and recommendations. *Sustain. For.* **2023**, *13*, 158. doi: 10.3390/su13101589
15. Alami, S.; Bouche, M.; Bouche, M.; Elzou, S.; Tasse, B.; Dwyer, A. Future trends in research manufacturing for low carbon building stocks: a prospective macro-scale analysis at the provincial level. *J. Clean Prod.* **2023**, *382*, 134738. doi: 10.1016/j.jclepro.2023.134738
16. Nadeem, M.; Khalid, A.M.; Jassim, E.; Hossain, S.; Hossain, S. Carbon footprint of low-energy buildings in the United Kingdom: effects of mitigating technological pathways and decarbonization strategies. *En. Trans. (Green)* **2023**, *4*, 100000. doi: 10.1016/j.enetrans.2023.100000
17. Alomari, S.A.; Alghamdi, S.S.; Alsharif, S.; Alghamdi, T.; Alkay, A.; Alsharif, S.S., et al. Benchmarking healthcare: the role of artificial intelligence in clinical practice. *WMJ. Med. Educ.* **2023**, *23*, 989. doi: 10.1186/s12960-023-04696-x
18. Liu, J.; Li, X.; Guo, Z.; Han, X.; Rong, P.; Wang, M., et al. Artificial intelligence versus precision medicine in cancer treatment. *Front. Oncol.* **2023**, *12*, 994822. doi: 10.3389/fonc.2022.994822
19. Sun, P.M.; Gohari, H.D. Security and privacy issues in smart cities/urbanization: technologies, applications, and challenges. *J. Ambient Intell. Human-Comput.* **2023**, *14*, 1957–1971. doi: 10.1007/s12233-022-00707-4
20. Kollman, M.; Graw, T.; Bröckling, S.; Maron, J. Conceptual model of key aspects of security and privacy protection in a smart City in Germany. *Sustain. For.* **2023**, *13*, 4926. doi: 10.3390/su13044926
21. Chaitin, R.K. AI-driven personalized treatment plans: the future of precision medicine. *Med. J. Soc. (2023)* **17**, 879–88.
22. Isomura, K.; Tsubota, T.; Saitoh, T. Potential for environmental impact reduction through building LC30 life cycle assessment of school facilities in material production stage. *Build. Environ.* **2023**, *238*, 110328. doi: 10.1016/j.buildenv.2023.110328
23. Nikarous, M.; Farina, R.; Sapienza, D. Life cycle assessment of steel-reinforced concrete: a systematic literature review. *Constr. Manag. Econ.* **2023**, *117*, 102000. doi: 10.1016/j.conmaneco.2023.102000
24. Tong, C.; Li, S.; Zhou, Y. Mitigating urban air pollution in university dormitory: the need for better ventilation and outdoor environment. *Buildings* **2023**, *13*, 1144. doi: 10.3390/buildings13011144
25. Jafar, J.; Naji, A. Improving indoor air quality through standardization. *Sustainability* **2023**, *15*, 245–257. doi: 10.3390/su15020245
26. Yilmazlar, T.; Barjasi, E.E.; Kucuk, I.; Sallakaya, A.; Hossain, S.; Mohamed, A., et al. Assessment of indoor environmental quality and seasonal well-being of students in a confirmed historic technical school building in Slovakia. *Environ. Monit. Assess.* **2023**, *193*, 1534. doi: 10.1007/s10661-023-12147-4
27. Agbada, O.T.; Alotado, B.; Dada, T.A.; Abiodun, M.A.; Abiodun, M. Built environment transformation in Nigeria: the effect of a regenerative framework. *J. Asian Arch. Build. Eng.* **2023**, *23*, 1–24. doi: 10.1080/13467581.2023.2238480
28. Guan, S.; Wang, J. Research on the optimal Design of Community Public Space from the perspective of social capital. *Sustain. For.* **2023**, *13*, 5957. doi: 10.3390/su13125957



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Behavioral city

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Behavioral City is a new concept that aims to integrate the behavioural approach of city policy making and the behavioural approach of urban planning. Behavioral Urbanism (BU) and its related area of study, behavioural architecture (Clara, 1977), is an interdisciplinary field focused on the interaction between humans and the built environment, studying the effects of social, cognitive and emotional factors in understanding the spatial behaviour of individuals. Behavioral Public Policy (BPP) is an approach to public policy that uses the tools of cognitive science and behavioural economics to identify how to change citizen behaviour towards individual and collective wellbeing goals.

KEYWORDS

behavioral public policy, behavioral urbanism, embodied cognition, nudge, urban planning, + boost, BRAIN

1 Foreword

Behavioral City is a new concept that aims to integrate the behavioural approach of city policy making and the behavioural approach of urban planning.¹

Behavioral Urbanism (BU) and its related area of study, behavioural architecture (Clara, 1977), is an interdisciplinary field focused on the interaction between humans and the built environment, studying the effects of social, cognitive and emotional factors in understanding the spatial behaviour of individuals.

Behavioral Public Policy (BPP) is an approach to public policy (Thaler and Sunstein, 2008; Thaler and Sunstein, 2021; Oliver, 2017; Viale, 2018a; Viale, 2021; Viale and Marchi, 2021) that uses the tools of cognitive science and behavioural economics to identify how to change citizen behaviour towards individual and collective wellbeing goals.

The gap that exists between these two approaches limits the optimisation of behavioural insights (BI) that are developed by both. The BI is applied downstream of the urban planning of the city decided by the policymaker. Its function is therefore to study the behavioural effects of an urban structure decided on according to non-behavioural variables. The urban plan of a city is in fact designed according to engineering criteria and based on political and economic negotiations. There is generally no BI evaluation of the effects of choices on the behavioural change of citizens and their wellbeing. BPP is a new approach and has so far not focused on urban planning. It has dealt with a range of public services such as sports, education, health, leisure, and social inclusion, which have an obvious impact on the spatial design of the city. The integration, however, of the two dimensions has so far never taken place practically or been thought out conceptually.

In the remainder of this article, I will try to highlight the conceptual and applicative aspects of Behavioral City.

¹ The article has been submitted by Herbert Smith Freehly.

2 The coffee maker of the masochist or the sadistic designer?

In *Sciences of Artificial* (1988), Herbert Simon's conception of design as "devising courses of action to transform existing situations into preferred situations" recognised its ability to create change. Since then, the role of design in influencing human behaviour has been widely recognised. It is also recognised that design in its various forms, whether as objects, services, interiors, architecture or environments, can create changes that are both desirable and undesirable, intentional and unintentional.

Desirable and undesirable effects are often closely intertwined, so that the former is usually intentionally designed, while the latter may be an unintended effect. For example, the impact of cars has been profound in improving social mobility on the one hand, while transforming cities and increasing demand for resources and pollution on the other. The former is generally considered a positive effect. The impact on the city of road construction, however, has largely had a detrimental effect on the environment and quality of life. In addition, the use of resources and pollution associated with cars and their infrastructure have prompted a rethinking of human behaviour and the technology used, as part of the sustainable design movement, resulting, for example, in programmes promoting less travel or alternative transport such as trains and cycling. Similar effects, sometimes desirable, sometimes undesirable, can be observed in other areas, including health, safety and the social sphere. For example, mobile phones and computers have transformed the speed and social code of communication, leading not only to an increased ability to communicate, but also to increased stress levels with a wide range of health and safety impacts.

Behavioural design is a sub-category of design. It concerns the way in which design can shape or be used to influence human behaviour. All design approaches for behavioural change recognise that artefacts have an important influence on human behaviour and/or behavioural decisions. They rely heavily on theories of behavioural change, including the division into causal variables related to personality, behavioural contingency and environmental context. Areas where design for behavioural change has been most commonly applied include health and wellbeing, sustainability, social inclusion, and crime prevention.

Design for behavioural change developed from the work in design psychology (or behavioural design) conducted by Don Norman in the 1980s. Norman's "psychology of everyday things" introduced concepts from ecological psychology and human factors research, such as affordances, feedback and mapping, to designers. They provided guiding principles regarding user experience and the intuitive use of artefacts, although this work has not yet focused specifically on their influence on behavioural change.

2.1 Affordances

The design of any physical environment or object is more or less conducive to human interaction. Norman refers to the concept of "affordance" (Gibson, 1977). According to Norman, "the term 'affordance' refers to the perceived and actual properties of

the object, primarily those fundamental properties that determine how it might be used. Affordances provide strong clues as to how things work (Figure 1). Plates are for pushing. Knives are for cutting. Slots are for inserting objects. Balls are for throwing or bouncing" (Norman, 1988).

The term "affordance" indicates an invitation, an authorisation that the physical object communicates to the user. It is the relationship between the object's properties and the user's ability to use it. It is, therefore, an inherently relational concept. Our direct perceptual capacity through the five senses and the bodily modalities of embodied cognition (see Section 3) allows us to relate to the affordances offered by the object. There are different affordances:

- A false affordance is an apparent affordance that has no real function, in the sense that the actor perceives possibilities for action that are non-existent. A good example of a false affordance is the placebo button.
- Affordance is said to be hidden when there are possibilities for action, but these are not perceived by the actor. For example, when looking at a shoe, it is not apparent that it can be used to open a bottle of wine.
- Affordance is said to be perceivable when information is available such that the actor perceives and can therefore act on the existing affordance.

2.2 Significant

While affordances determine which actions are possible, the signifiers of an object communicate where the action is to be performed. This semiotic concept "points to any visual or auditory cue, any perceptible indicator that communicates what the appropriate behaviour is" (Norman, 1988, p. 31). People need to understand how to use an object so they rely on clues or messages that indicate how to use it. Signifiers can be intentional like a sign telling us to pull on a door handle. They can also be unintentional like the trail left on the lawn by students on a campus signifying the dense path to get from one area to another. Affordances are perceived or unperceived possible interactions, while signifiers are perceived signals that express possible interactions and how to activate them.

2.3 Mapping

Mapping is a term for the relationship between the elements of two sets. This concept is important in the design and layout of controls and displays. When mapping uses the spatial correspondence between the location of the controls and that of the controlled devices, it is easy to understand how to use them. The example in Figure 1 of the alternatives for commanding gas nozzles in a kitchen illustrates the possible differences in the clarity and intuitive ease of understanding the correspondences. Intuitive mapping is that which exploits analogies and spatial proximities. Some mappings are cultural, while others are derived from the principles of perception as studied by gestalt psychology.

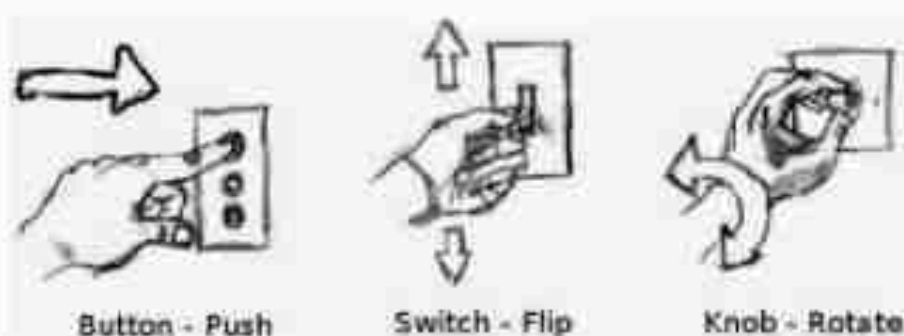


FIGURE 1
Affordances of light switches.

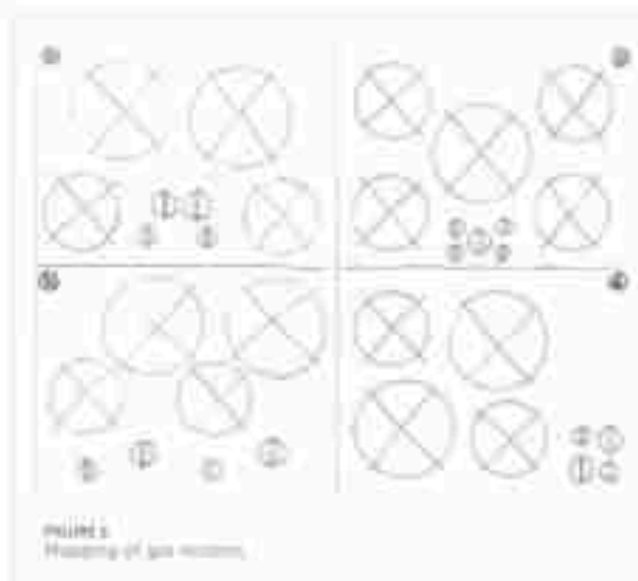


FIGURE 2
Mapping of gas meters.

2.4 Feedback

A feedback mechanism is based on information about the effects of our action. Its characteristics are related to the detail of the information and its timeliness. If the information is well-calibrated, frugal, meaningful and timely, it generates real learning in the subject. If, on the other hand, it is generic, redundant and slow, it can have a counterproductive effect. As we shall see later, one of the most effective behavioural tools in public policy (e.g., energy saving) is precisely the introduction of effective feedback systems.

Norman's aim is to propose an anthropocentric or "human-centred design" that starts from human needs, capabilities and behaviour and adapts the design to them. This type of design starts with knowledge of psychology and technology.

Norman's original approach explored ways of influencing behaviour, such as "emotional design" and "persuasive technology." Since 2005, a number of theories have developed that explicitly address design for behaviour change. These include a variety of theories, guidelines and tools for behaviour change covering the different fields of health, sustainability, security, crime prevention and social design. The emergence of nudge theory (Thaler and

Rischtein, 2008) and behavioural public policy approaches are the most important consequences of behavioural design.

3 The model of the mind

"Behavioural design" or "design for behavioural change" to work must be based on a model of mind that corresponds to the empirical reality of the causal relationship between mind and behaviour.

For many years, the behavioural sciences have referred to a computational conception of the mind. According to it, the mind can be likened to a Turing Machine that works in binary mode and processes information that arrives from the environment. The computer metaphor has been the prevailing one: the mind is *in software* as the brain is to computer hardware. Information processing psychology, which was the dominant theory of cognitive psychology, was based on these conceptual premises. It was ultimately a Cartesian-type conception of the mind that had the following characteristics: there is duality between mind and brain, the mind is modular, i.e., cognitive functions are specific, vertical, localized and impervious to cortical influences; representations are amodal, i.e., neutral with respect to emotional, sensory, motor and visceral modalities; thought corresponds only to digital computation; the mind is separate from the body and the environment that surrounds it. This model is also called classical cognitivism (Pavulli Palmatieri, 2008) and has been the basis of behavioural economics and the work of leading scholars from Nobel Prize winners Herbert Simon, Daniel Kahneman and Richard Thaler to cognitive scientists such as Noam Chomsky and Howard Gardner.

Herbert Simon actually has a more open view of the role of the environment in decision making. In fact, he illustrates the bounded rationality of human behaviour with the metaphor of *acorns* (Norman, 1998): deciding derives from the convergence of two blades, one representing the limited computational characteristics of the human mind and the other the complexity, uncertainty and limitedness of environmental information. The blade of cognition is therefore not enough to decide, but it is only from the dynamic interaction of cognition and environment that human behaviour unfolds. It is precisely this metaphor, however, that introduces the missing element in classical cognitivism.

The two blades of cognition and environment can interact and succeed if the pivot is present that allows them to coordinate

(Viale, 2018a; Gallwey et al., 2021). The pivot is represented by the body. This is the perspective of embodied cognition: cognition is not in a separate bubble from the body, but is in fact embodied with it and our capacity for thought and judgement is intimately linked to and shaped by action. It is no longer the body that is at the service of the brain as traditional cognitivism claims, but rather the opposite, i.e., the brain is the tool that enables the individual to physically interact with the environment. The very centre of gravity of the decision-making process at this point is no longer located in the cognitive computational part, but shifted to the pragmatic part, of the possible actions that the environment allows.

Cognitivism had represented the thinking and deciding mind as being separate from the body and the environment. The mind is “disembodied” from the body that carries it and “disengaged” from the environment in which it interacts. Instead, the new perspective introduced by neuroscience refers to “embodied” and “grounded” cognition. That is, cognition integrated with the body through action and shaped by the environment with which the body interacts. The acting body should no longer be understood as a mere physical tool driven by the mind, as if it were the physical structure of a robot driven by its software. Instead, the body is now with cognitive activity and together they interact with the environment. Through this interaction we acquire motor and perceptual experiences that are subsequently mediated by cognition. Body states are, therefore, also necessary for cognition to simulate perceptual and motor experiences, sensorimotor patterns (“patterns”) that are extrapolated from their motor function and explored in cognitive processes other than those for which they were created (Gallwey and Goldman, 1996). Let us consider, for example, the importance of simulation in our social activity, in our interaction with others, in decisions about what to do in a group work or in a market in which several parties operate. In these cases, we decide after reading the minds of others through bodily simulation of their possible actions and the resulting affective and emotional outcomes. These simulations are based on the reactivation of sensorimotor experiences previously acquired by the individual in similar contexts (Gallwey et al., 2004; Jacoboni, 2008). The same argument applies to the interaction of individuals with physical spaces. People behave through the simulation in their bodies of their possible actions and the resulting affective and emotional outcomes. The core of the decision-making process is, therefore, no longer located in the computational and cognitive part, but has moved to the pragmatic part, of the possible actions that the body-environment interaction allows. This position that places the constraints of rational choice and decision-making activity not so much in the computational possibilities of the human mind as in the mind-body-environment interaction represents a further development of Herbert Simon’s theory of Bounded Rationality. The environment cannot only be analysed as the structure of the task according to its cognitive computational variables. The physical and social environment also generates sensory, visceral and motor constraints that influence reasoning and decision-making (Damasio, 1994). In determining a choice, possible and simulated bodily actions influence the range of possible options and the value attributed to them.

As is explained in Viale et al. (2023b), I consider embodied cognition in a broad sense to include what has been termed 4E (embodied, embedded, extended and enactive) cognition (Newen et al., 2018). From this perspective, the body’s neural

and extra-neural processes, as well as its mode of coupling with the environment and the resulting environmental feedback, play an important role in cognition. Wilson (2002) outlined a set of principles supported by most 4E cognition theorists:

1. Cognition is situated
2. Cognition is under time pressure
3. We rationalise cognitive work on the environment
4. The environment is part of the cognitive system
5. Cognition is for action
6. Cognition (in both basic and higher order forms) is based on embodied processes

Proponents of 4E approaches (Gallagher, 2018), however, vary in what they emphasise as explanatory of cognition. The body can play different roles in shaping cognition. Enactive approaches emphasise the idea that the body is dynamically coupled to the environment in important ways (Thompson, 2007; Di Paolo, 2008); they point not only to sensorimotor contingencies (where specific types of movement modify perceptual input) (O’Regan and Noë, 2001), but also to bodily affectivity and emotion (Coleman, 2014) as playing a non-representational role in cognition. Integrated and enactive approaches emphasise possibilities for action that are related to the body and abilities (Chomsky, 2000). Regarding the idea of problem-solving, there is general agreement that the environment constitutes the scaffolding of our cognitive processes and that our involvement with the environmental structure and features, including external supports and devices (such as a pocket calculator or an underground map), can shift the cognitive load. Already, in the context of Simon’s work, it is clear that only through the active interaction between problem solver and environmental affordances it is possible to construct a behavioural solution (Viale et al., 2023a). The metaphor of the ant on the beach is illuminating (Simon, 1988): imagine an ant walking on a beach. In Simon’s parable, it is not possible to understand the ant’s behaviour simply by looking at it. Seen as a geometric figure, the ant’s path is irregular, complex, difficult to describe. But its complexity is actually the complexity of the surface of the beach, not that of the ant! (Simon, 1988, 1990, reprinted 2019, p. 80). In other words, to predict the ant’s path, we must consider the effects of the beach, i.e., the context of affordances in which the ant operates. The message is clear: we cannot study what individuals want, need or value separately from the context of their environment. That environment shapes and influences their behaviour. In this example, the ant’s procedural rationality (finding appropriate behaviour on the beach) requires its substantive rationality (adaptability to the irregularity of the beach’s affordances).

According to Simon (1996), environmental feedback is the most effective resource for shaping human actions in solving a problem. Design activity is modelled by the logic of complex feedback. In planning, one pursues a purpose, which is to solve a given problem (e.g., designing a homogeneous urban plan for road traffic regulation), and when one thinks one has achieved it, feedback is generated (e.g., from the political world or the social or natural environment) that introduces a new and unexpected purpose (e.g., energy-saving constraints). This leads to reworking the plan and generating new retroactive effects. The same selectivity in solving a problem is based on feedback from the environment (Simon, 1964; Simon, 1990, p. 2018).

Simon and Newell (1971) propose the notion of problem space. They write (p.150) a “problem space concerns the possible situations to be searched for in order to find that situation that corresponds to the solution.” The concept of problem space can easily be characterised in terms of active interaction and coupling with environmental availabilities. A problem space is equivalent to the possible solutions that can be implemented in relation to the presence of affordances (Barfield and Kieras, 2014). Some of the resources that define a solution will come from past experience and one’s own skills, others from the consequences of the actions attempted to reach the solution. The actions that lead to the solution transform the world in a recursive feedback process.² Indeed, for Simon (1968), Simon (1990, p. 231, the distinction between “state description” that describes the world as it is and “process description” that characterises the steps in manipulating the world to achieve the desired end is important.³ The correspondence between action and solution of a problem conceptually bypasses the analytical phase of the decision and limits the role of symbolic representation. In solving any problem, be it opening a door, running to catch a falling ball, replacing a car tyre, calculating a financial investment, solving tests and puzzles or negotiating with a competitor, the search for the solution corresponds to acting in the sense of embedded cognition 4b, including the idea of a recursive feedback process leading to the final action. From this perspective, the concept of “enactive problem solving” synthesises the integration of multiple factors and may well represent the complexity of the phenomenon (Vale, 2024).⁴

For the idea of enactive problem solving, however, it is important to emphasise two things (reference to Vale et al., 2023a). First,

2. Although problems, problem processes, which often add those attempting to solve the problem, seem a kind of, are of, formal systems.
3. To use another Simon (1968, p. 230) quote, “the art is to find the developing state” (Simon, 1968, 2000, continued 2003, p. 232). The search space, through successive states with decreasing/qualifying feedback, does, indeed, find solutions directly towards the final goal, but this happens not only when the problem is not well structured, as in the case where we do not have the information of a target, but also when we have the necessary information.
4. The importance of the embodied aspects of human cognition that emerge from the concept of enactive problem solving (Vale et al., 2023a) can also be demonstrated in the debate generated by the debate features stated within the ecological rationality programme (Gigerenzer et al., 1999; Gigerenzer et al., 2021). Ecological rationality represents the direct development of bounded rationality (Simon, 2003a). Most features of ecological rationality normally have to do with decision-making, but it really does offer active problem-solving mechanisms that can be applied to types of embodied cognition (Gigerenzer, 2022). In support of this, there are at least three main empirical studies that illustrate active rationality. The case formal studies called by Gigerenzer include recognition memory, frequency tracking and, in addition, three formal embodied cognitive studies, visual object tracking, memory and intuition (Gigerenzer and Gigerenzer, 2022; Harbeck and Hoffrage, 2012; Harbeck and Harbeck, 2008).

the relational nature of affordances. It is not only the environment that constrains behaviour; it is also the body’s morphology and motor possibilities, as well as the agent’s past experience and skill level that will define what counts as an affordance. How the body couples (or can couple) with the environment will delimitate the set of possibilities or solutions available to the agent. Similarly, affordances may also be limited by an agent’s affective processes, emotional states and moods. Sometimes it is not just what I “can” do (given my skill level and what the environment offers), but what I “feel like” (or don’t feel like) doing (given my emotional state).

Secondly, as pragmatists point out, the environment is not only the physical environment; it is also social and cultural and characterised by normative structures. As Gibson (1968), Gibson (1976) pointed out, affordances can be social. Enactive problem solving also highlights the important role of social and intersubjective interactions. Once again, it is not just a question of what “I can” do, but also what “I cannot” (or “should not”) do given normative or institutional constraints, as well as cultural factors having to do with, for example, gender, race and social groups (think of the role of public spaces in processes of social inclusion). These are broader issues ranging from understanding how dyadic interactions shape our developmental capacities, to how institutional factors may enable or constrain our social interactions.

4 Behavioral design of public policies

Following the success of the book *Nudge* (Thaler and Sunstein, 2008) and the creation of the BCT in the British government by James Cameron and the Social and Behavioral Sciences Team in the White House by Barack Obama, behavioural design is gaining ground in public policy-making at state and local levels. In various parts of the world, city governments increasingly refer to behavioural analysis to design public policies that are more effective in achieving the administration’s goals and improving citizens’ lives.

What is meant by behavioural analysis of public policies (reference to Vale, 2018a; Vale and Maschi, 2021; Vale, 2023)? In general, public policies are developed and analysed with the tools of law and economics. In particular, the priorities for policymakers are inductive consistency with regard to the formal legal framework of reference and cost-benefit analysis for the economic estimation of policy effects. The objectives are generally of a political nature, i.e., either linked to the explicit or implicit interests of the electorate of reference or the parties supporting the government, or linked to their cultural and value constraints that influence the type of policy adopted. Behavioural analysis adds a new dimension to policy design. That of the cognitive and decision-making feasibility of the objectives incorporated in the policy. Behavioural analysis asks to test on a psychological level which policy instrument can be most effective in achieving the policymaker’s goal, given equal legal, economic and political conditions. Testing on a psychological level means identifying empirically or by analogy with other situations whether an instrument has the capacity to bring about the desired change in citizens and public and private organisations. Knowledge of a set of behavioural regularities of the individual, when in certain contexts of choice, would allow the policymaker to simulate ex-ante the effects of regulations and calibrate them in relation to the desired effects. Simulation can be done both theoretically and

by analogy with similar situations. Or it can be tested empirically through laboratory experiments, surveys and limited interventions in small samples of the population. In the first case, we will have a 'behaviourally-informed' policy initiative (European Union, 2016), i.e., built on prior knowledge and empirical behavioural evidence. For example, in Europe the warnings against smoking in cigarette packaging was introduced without prior testing, but based on knowledge from communication psychology. Or the ban on "pre-checked boxes" in the online booking of planes or other consumer platforms. In the second case, one could instead speak of "behaviourally-tested" initiatives (European Union, 2016) as the evidence would be sought in *ad hoc* empirical studies. An example is the EU recommendations on gambling that were derived from *ad hoc* experimental studies. Or the work on "tax compliance" done by the Behavioral Insights Team (BIT) in London in which certain "frames" describing the correct behaviour of other taxpayers, were introduced in letters reminding them to pay their taxes (Halpern, 2015; Halfon and Kirkman, 2020). Obviously, one is often faced with policy measures that do not fall into either category, but which, in any case, manage to match and interpret, unconsciously, certain behavioural propensities of the individual. In these cases, the appropriate term might be "behaviourally-aligned" (European Union, 2016). A significant example of this was the regulation on nutrition and health claims introduced by the Commission in 2006 (European Commission, 2006), which included a ban on the use of misleading frames (such as only stating the percentage of non-fat and not also the percentage of fat in food).

If behaviour change is the ultimate goal of the policymaker, we have to consider that it is possible when a number of variables at both the individual and contextual level are met. According to Michie et al. (2013) capability, opportunity and motivation interact to generate behaviour that, in turn, influences these same components (the "COM-B system"). Michie et al. (2013), p.4 write: "Capability is defined as an individual's psychological and physical ability to engage in the activity in question. It includes the necessary knowledge and skills. Motivation is defined as all those brain processes that energise and direct behaviour, not just goals and conscious decision-making. It includes habitual processes, emotional responses and analytical decision-making. Opportunity is defined as all factors external to the individual that enable or drive behaviour. There are potential influences between the components of the system. For example, opportunity can influence motivation as well as ability, enacting a behaviour can alter ability, motivation and opportunity" (Michie et al., 2013, p.4).

The COM-B system has attracted some criticism for its rather poor psychological articulation. It is, however, a useful scheme that could be refined to develop a behavioural change model for policy-making (Vais, 2021c). The three categories can in turn be further subdivided into subcategories and articulations of them. Consider opportunity: it includes both the physical and symbolic environment, thus all forms of choice architecture in libertarian paternalism, but also legal constraints and norms or economic incentives and the cultural and social background that binds individual choices and behaviour.

In the Behaviour Change Wheel (Figure 3), the causal action on the three categories of behavioural change variables does not occur through policies, but through an intermediate step represented by interventions. As argued by Michie et al. (2011), "it was necessary



to make a distinction between interventions (activities aimed at changing behaviour) and policies (actions by responsible authorities that enable or support interventions)" (Michie et al., 2011, p. 6).

Public policy in this context is not seen as an objective, e.g., reducing tax evasion or increasing energy savings, but as an instrument at the disposal of the policymaker, e.g., a measure or regulation or tax legislation. For example, if the objective is to improve tax compliance, the policy instruments may be tax related, e.g., reduced tax rates, or legislation related, e.g., increased penalties for tax evaders, or communication related, e.g., descriptive social norms (Cialdini, 2001; Cialdini and Goldstein, 2004; Cialdini et al., 2006) used to inform citizens about the virtuous behaviour of their neighbours. The first will appeal to the *intervention* mode of incentive; the second to coercion; the third to information. The same policy objective can be achieved with different instruments, which in turn can provide different modes of *intervention*. Interventions, in turn, may influence one or more determinants of behaviour.

An environmental restructuring intervention concerning the choice architecture of a supermarket, where unhealthy food is placed on the highest shelves, affects motivation by decreasing the perceptual salience of the product as well as the opportunity, making unhealthy food difficult to reach. A persuasive intervention concerning a descriptive social norm promoting compliance in a public park mainly relies to motivation, as it activates automatic social imitation mechanisms. In the case of complex objectives such as combating a pandemic, many policies and interventions are referred to in order to influence all sources of behaviour.

According to some authors (Lorusi and Moroni, 2020; Lorusi and Moroni, 2022), behavioural change can also be achieved by an approach called "Riding without Rules" using ademonic artifacts that are material objects that do not have a normative function as such. For example, the sleeping policeman that has the role of speed bump to slow traffic or the pillars at exits from places (such as football stadium) in which large flow of people usually leave.⁵

⁵ It is not clear the intended mission of the designers of ademonic artifacts. For example, the road police authority that proposed the sleeping

In order to be effective, behavioural design must pivot on a realistic model of cognition, that of embodied cognition and enactive problem solving that I outlined earlier (Viale et al., 2023a). Indeed, the application of behavioural sciences and in particular behavioural economics to generate the behavioural change desired by policymakers often does not achieve satisfactory results due to the inadequacy of their behavioural model (Maise et al., 2022; Viale, 2022).⁶ Behavioural change can be achieved by designing choice architectures inspired by embodied cognition and the behavioural model of enactive problem solving. In fact, the term choice architecture is introduced in the book *Nudge* (Thaler and Sunstein, 2008) referring precisely to the concept of affordances underlying the thesis of Don Norman's brilliant book *The design of everyday things* (1988). The architect acts as a designer to introduce the right affordance into a given environment, so that a subject is prompted to act in a certain way. Affordances do not necessarily have to be physical objects. They can also be symbolic. Even with language and social norms, chosen environments can be designed to allow embedded knowledge to interact with the individual according to the architect's plan.

Thaler and Sunstein correctly refer to affordances as the pivot for generating choice architectures capable of bringing about behavioural change. But they do so incompletely by referencing an unworkable decision-making model subordinated to traditional cognitivism. How is it possible to identify choice architectures that incorporate a 4E theory of cognition? One answer is to create choice architectures that activate a dynamic of active coupling ("coupling") between the offerings of the subject and the environment. To do this, the behavioural stimulus must refer not only to the computational cognitive aspects of the human mind but also to the bodily, affective, sensorimotor and visceral dimensions and the specific social situation in which the subject is embedded. Below are some examples of "embodied cognitive nudging" that can be applied in the context of urban public policy.

4.1 Social norm⁷ (role of embodied and embedded cognition)

A descriptive social norm is most effective if it generates an embodied simulation of the described behaviour by the subject. To do this, the norm must refer to real subjects who have had an

embodied experience in their situational reality, whose behaviour is easily simulated on a sensorimotor and affective level, whose pragmatic purposes are the same as the subject's or at least can be easily induced by the norm. An example from Goldstein and Cialdini's work is the experiment on how to convince customers of various Artana hotels to reuse towels (Goldstein et al., 2008). The aim of the study was to understand how adherence to a descriptive norm varied in relation to the type of reference group included in the norm. The norms were divided into "provincial" norms, i.e., those describing the behaviour of customers in the hotel where the subjects of the experiment stay (e.g., those who had stayed in the same room before) and "global" norms, i.e., customers whose behaviour is further removed from the subjects' physical and decision-making context (e.g., other hotels in the area or state). In addition, the study sought to analyse which reference groups were most effective in triggering compliance with the norm. In social psychology there are generally two categories that seem to have the greatest influence on behavioural norm compliance. The first is the level of perceived similarity with others (Festinger, 1957). The second is the degree of identification with the relevant social group. If a social identity is perceived as salient, individuals tend to adhere to it based on its importance and relevance. Goldstein and Cialdini's study introduces a new explanatory category: situational similarities. Situations are powerful behavioural determinants. For example, the rules that apply to a party situation among friends do not apply to a work situation; even in the case of marked social identity or perceived similarity to others. The logic of the situation in which we find ourselves conveys the reasons, determines and affects the meaning of our actions, so it is an important factor in establishing the relevance of descriptive rules. In other words, if I know that someone has been in the hotel room I am in, this will generate a strong focus on what they did and how they behaved. This is even more relevant than other references to the behaviour of social categories that are important to me or of people who are similar to me, but whom I perceive as more abstract and emotionally distant than a person moving in the same space in which I find myself. The results of this and other experiments lead to a number of fundamental reflections. Clearly, the situational similarity of the "provincial" norm has no greater informational value than that of social belonging, such as gender or citizenship. However, the "provincial" norm generated more emotive effects on the reuse of towels than the other information. Why do we attach more informational relevance to sharing our surroundings - such as a hotel room - rather than to more meaningful similarities, such as social and cultural similarities, or those that we may share with the large number and variety of guests in the hotel? There could be an ecological and adaptive reason. What we do in a specific environment is often dictated by the experience of others in that same environment. If we want to orient ourselves on how to behave in an unfamiliar situation, it will be very useful to know what other people have done in that same context. When we have no experience of a given environment, we rely on the experience of others who have been there. The built-in adaptive dimension of this behaviour is evident. Blindly experiencing new situations could have proved fatal for our ancestors. It is better to value the experience of others. As an inhabitant of an ecological environment, I am inclined to feel close to those who have lived there before and thus to value their choices. Another reason could be the one identified by the social

⁶ Evidence of choosing politicians that the evidence must be used for (Micaletti).

⁷ There are many key reasons for this. The first is that they depend contextually and methodologically on the abstract norm model of the Subjective Expected Utility (SEU) theory. The second reason is that they express a Cartesian and individualistic conception of the human mind, which does not support the idea of the body and the environment and its effects on understanding the real drivers of behavioural change (Viale, 2024).

⁸ According to Lave and Wenger (2000), a social norm is a behavioural rule. This is not true because the descriptive social norm-making is a typical instrumental policy making that aims to change the inferred context relying on evidence of the behavior of peers or of some popular "leader" (Viale et al., 2023a, Viale, 2023a).

psychologist [Hinder \(1998\)](#), even small and insignificant similarities can create a sense of unity between different people. It is important that these similarities are rare and uncommon, i.e., not shared by the majority but only by a few. Clients of an hotel's room share the same experience with only a few people before them. This makes them feel closer to each other and thus they are likely to perceive the description of their behaviour (i.e., the "provincial" norm) as salient and meaningful.

The use of social norms can be enhanced by urban plans that allow the creation of communities of citizens who share problems and solutions in neighbourhood management. The construction of small urban communities can only result from certain architectural and urban typologies that push towards social interaction and inclusion. For example, non-uniform buildings and the presence of public spaces that are inviting and attractive due to the availability of services and greenery. This may promote the generation of social capital which, as the [World Bank \(2015\)](#) analysis explains, is the precondition for the functioning of social norms as a tool of the policymaker for behavioural change. We saw this phenomenon clearly during the emergence of COVID-19 where the effect of nudging based on social norms, such as describing the correct behaviour of neighbours in following distancing and hygiene precautions or presenting these norms to safeguard the wellbeing of their community, only worked in urban realities marked by social capital.

4.2 Feedback (role of enactive cognition)

One of the most important nudges concerns the effects of one's choices ([Thaler and Sunstein, 2008](#); [Viale, 2022](#)). It is well known that the most effective way to improve our judgement and decision-making abilities is to learn from our mistakes and experience positive or negative outcomes. One of the reasons for augmenting feedback is not only that we can learn from mistakes so that we do not make choices that will turn out to be wrong. An important reason is that we can inductively improve our theories about the world, i.e., we can improve our prediction of future states of the world, for example, when choosing an investment, a school and a political party. Choice architectures aimed at increasing feedback can be designed in two ways. The first is the corrective response of the environment to an error we are making. This can be done a priori, when the environment has already incorporated mechanisms to neutralise our propensity to make a mistake (e.g., retrieving the ATM card before withdrawing money) or retrospectively, when the decision-making process is blocked and the mistake is identified (e.g., when we buy something online or fill out online questionnaires or payment forms). The second is the introduction of feedback mechanisms on our choices in order to generate learning and corrections. Numerous examples can be found in environmental policy. The use of e-mails or text messages in California to inform households about their energy consumption has not produced great results ([Thaler and Sunstein, 2008](#)), but the introduction of detectors such as the Ambient Orb - a small luminous sphere that turns red when consumption is excessive and green when it is acceptable - has proved more effective. The introduction of this simple device resulted in energy savings of up to 40 per cent. Another successful mechanism is the Watson display that records

our consumption patterns and compares them with those of other users. When the comparison takes place mainly with neighbours, feedback together with social imitation become powerful behaviour correctors ([Viale, 2022](#)).

A feedback architecture inspired by the "enactive" features of cognition can enhance its role as a nudge. The enactivist part of embodied cognition emphasises the idea that perception is for action and that this action orientation shapes most cognitive processes ([Gallagher, 2017](#), p. 40). Cognition is distributed between brain, body and environment. How to explain this dynamic coupling? According to [Van \(1997\)](#) and [Gallagher \(2017\)](#), nonlinear dynamical systems tools and methods can be used to capture the dynamic coupling between body and environment. Perception itself depends on sensorimotor capabilities and possibilities. [Gallagher \(2017\)](#) writes:

"Perception is a pragmatic exploratory activity mediated by movement or action and bound by contingency relationships between sensory and motor processes. One can think of this in terms of ecological psychology, where perception of the environment includes information about one's posture and movement, and one's posture and movement will determine how one experiences the environment." ([Gallagher, 2017](#), p. 41)

According to [Merleau-Ponty \(1962\)](#), when an agent acquires skills, these are "incised" not as representations in the mind but as a bodily readiness to respond to the demands of situations in the world. If the situation does not clearly prompt a single response or if the response does not produce a satisfactory result, the subject is led to further refine his simulations which, in turn, prompt more refined responses. Merleau-Ponty calls the feedback loop between the embodied agent and the perceptual world an attentional arc. Describing the phenomenon of everyday coping as an "insertion" into the world and a movement towards "equilibrium" suggests a dynamic relationship between the subject and the environment. [Van Gelder \(1997\)](#) calls this dynamic relationship coupling. Also according to [Sutton \(1990\)](#), environmental feedbacks are the most effective in shaping human actions in solving a problem. Urban planning itself is shaped by the logic of feedback. In planning, a purpose is pursued, which is to solve a given problem (e.g., designing public spaces that promote social inclusion) and when it is thought to have been achieved, feedback is generated (e.g., from the world of social welfare organisations) that introduces a new, unforeseen purpose (e.g., architectural barriers for the handicapped or noise pollution for neighbourhood residents). This leads to reworking the design and generating new retroactive effects. The same selectivity in solving a problem is based on the feedback of information from the environment ([Sutton, 1998, 1998](#), reprinted 2019, p. 218).

Feedback in social interaction implies a reciprocal dynamic and active responses to the other's action, viewing the action as an affordance for further action. This feature of social affordances can be viewed not only bilaterally, but also multilaterally. In other words, the concept of "I can" ([Hassard, 1999](#)) can also become that of "we can" ([Viale, 2022](#)). If in my engagement with others my enactive response is shaped by my membership in a social group, it will also be calibrated by reference to the action of other group members.

An enactivist approach to nudging explains how important it is to be specific in feedback loops and how crucial it is to understand the embodied dimension of coupling. Indeed, feedback does not always lead to behavioural improvements. For example,

numerous studies on school learning have shown that when dealing with incorrect answers from students, the use of generic feedback regarding the correctness or inaccuracy of the answer did not have a positive effect on learning. More specific feedback is needed, namely, telling the student what the correct answer is in the specific case. By analogy, nudging should also focus on designing choice architectures that provide feedback that is not superficial or generic, but aimed at stimulating the behavioural compliance pursued by the policymaker. In other words, taking the Ambient Orb example, learning feedback would provide information on which appliances consume too much and even propose specific alternative solutions on how to reduce it.

Feedback mechanisms such as error neutralisation could also inspire urban planners. Just think of road design, especially of highways. Intuition often leads us to take the wrong road. When road design does not incorporate this possibility, the motorist finds himself travelling kilometres before finding a way out and returning to the wrong exit point. A planner who wants to incorporate error neutralisation, on the other hand, anticipates these possible defaults and allows correction after a few hundred metres. An urban planner and an architect who wants to emphasise the role of feedback in improving citizen wellbeing designs an environment rich in information about the effects of human actions. For example, through the widespread installation of devices to assess energy, gas and water consumption, to measure one's own body weight, etc.

4.3 Reminders and prior engagements (role of extended cognition)

At least two nudges are based on extended cognition. As argued by Jon Elster in "Ulysses and the Sirens" (1979) and in several of his books, one of the most systematic pathologies of rationality is weakness of will (or akrasia). This emotional pathology, studied by behavioural economics, leads us to procrastinate in making choices that we think are right for our wellbeing and social welfare. Although we would like to, we fail to save money, eat healthy food, exercise regularly, keep informed, stop smoking or drinking, etc., and what is worse is that we fail to find time to be with our children, fail to visit our elderly parents and neglect our partner. To overcome our weak will, just like Odysseus had himself tied to the mast of the ship to escape the sirens' call, we can rely on the so-called System 2⁸ of the mind to reduce our freedom of choice, i.e., to adhere to some "pre-commitment" measures. These measures are easier to adopt when the asset to be pledged comes from outside (a salary, a bank) e.g., by scheduling automatic withdrawals from our monthly income that we can agree with the bank. We agree with the external actor providing the asset, to give up a piece of our sovereignty, to take away part of our income and move it to another fund. Finally, a very useful information boost comes from reminders. Reminders act as alarm

bells on deadlines and obligations, making decision-making easier for people and enabling them to avoid fines and penalties. Thanks to new technologies, reminders have become extremely common, but the downside is an increased risk of the "cry wolf" effect if their frequency exceeds our threshold of attention and tolerance. Even if reminders are informationally correct, people will tend to overlook them, putting them off until the next reminder. With this in mind, it is better to set only one reminder and not more than one deadline, and to activate it at the right time (not too far in advance, but also too close to the deadline).

Both nudges are examples of decision-making functions that are outside our minds and help us improve our wellbeing. They are an example of how a behavioural smart city could improve the wellbeing of its citizens by enriching their cognitive dimension with an extended help in the urban environment. An internet of things not confined to one's home, but extended into public spaces, public transport in public places. That allows reminders about activities of public interest or about deadlines for commitments or compliance or warnings about risks and dangers of public interest and appropriate behaviour to adopt.

4.4 Default options (contrary to enactive cognition)

The innovation introduced by Thaler and Sunstein (2008) in public policy was to address the automatic, unconscious mechanisms of the human mind (conveyed by System 1) for the benefit of the citizen's wellbeing (as determined by the policymaker). The idea was to exploit human flaws and turn them into advantages. Human beings are lazy, inert and short-sighted and this is often counterproductive. Nudges are based precisely on these suboptimal characteristics for the benefit of the citizen. Humans are subject to unconscious cognition illusions,⁹ called biases, such as the framing effect. Nudges use biases to nudge the citizens towards better wellbeing. There are many automatic, unconscious S1 mechanisms that can be used to benefit individuals and achieve a positive outcome. The default rules correspond to the nudge par excellence¹⁰ (and also the one that can most easily be interpreted as manipulation). The mechanism is very simple: if we do not make a choice, we find ourselves in a condition where the choice has been made a priori. In Austria, for example, the organ of a person who has not decided whether or not to be a donor will be harvested and transplanted into another person. In Germany, however, the organs of a person who has not decided on donation will not be harvested in the event of death. These are two opposite examples of default options regarding organ donation. According to the first, called opt-out, you are required to declare that you do not intend to donate your organs if you so wish. The second, called opt-in, requires donors to declare their willingness to donate their organs. As a result of

⁸ Reference is made to the *System 1* and *System 2* of the mind (described by Daniel Kahneman) which, apart from automaticity and non-consciousness and *System 2* of the mind characterised by active cognitive effort, awareness, will and awareness (Kahneman, 2011). The reference to S1 and S2 usually found has now a more technical, more specific (it really is technical) and interesting use (Duke, 2023; Vale, 2022).

⁹ The reference is the concept of Kahneman to define how biases emerge from the influence of Gestalt perception on the thought of Daniel Kahneman.

¹⁰ Default options are one of the most effective nudges (Thaler and Sunstein, 2008).

these opposing approaches, the organ donor rate in Austria is slightly above 90%, while in Germany it is below 10%.

Why are the results so different and why would it be necessary to introduce default options to achieve a public policy goal? According to *Thaler and Sunstein (2008)*, human beings tend to procrastinate and postpone choices and are slaves to inertia and laziness. We consider the status quo and the current condition as our optimal reference. We suffer from myopia and are unable to make proper assumptions and predictions about the future. These behaviours are the result of various mechanisms related to loss aversion ("if I act, I may suffer a loss with respect to the present"), or regret (regret for inaction is better than regret for action). Because of these mechanisms, individuals find it difficult to face choices that affect their wellbeing. For this reason, in order to paternalistically help individuals to improve their wellbeing and that of the community, the architects of choice have designed default status whereby even when we do not decide, an *a priori* decision is made for us that we could theoretically reject by opting out, i.e., abandoning the default option.

In *Vidali (2022)*, I criticise the neo-liberal dimension of default options. An interesting observation concerns the perspective of embodied cognition. Default options are effective because they reduce active coupling ("coupling") with the decision goal. They are "non-interactive" architectures of choice. By exploiting our inertia and procrastination they put to sleep the individual's active feedback loop with the choice context. They are, however, powerful behavioural tools that placed in an urban dimension could help the policymaker achieve his behavioural change goals more easily. Various may be the examples of urban default options. One example among many, the one for road safety in Cape Town, using the loss aversion mechanism, the government set up a lottery in that the virtual "ticket", i.e., the chance to participate in the prize draw, would be given by default, automatically, to all licensed citizens (and only to them) who at the beginning of the festive period had no record of driving offences. Drivers would then lose this "ticket" if they committed offences during the festive period. Payment for use of parking spaces, or public transport subscriptions, or active participation in public utilities, such as street cleaning and waste collection in parks, could be fixed by default with the freedom to opt out. Default options could also be incorporated into the urban architectural structure itself. One could conceive of architectures that correspond to the passive and inertial tendency of the citizen, thus favouring certain objective behaviours of the policymaker. In the objective of social inclusion, one could study quasi-automatic walking routes leading to public spaces, such as squares or multi-purpose cultural areas, attractive from the point of view of services, where one could confront initiatives of ethnic and social inclusion. With the aim of increasing healthy lifestyles and sustainable mobility, low-cost parking areas, away from homes, could be favoured to promote pedestrian mobility. The same could be done for the use of stairs instead of lifts, increasing the sensory attractiveness and accessibility of stairs and decreasing the use of lifts. The same logic of default could inspire an urban planner in the design of streets. Default routes could be introduced to move from one part of the city to another that have less noise and pollution impact on inhabitants. The motorist would find it easier through attractive and persuasive signage and better flow to automatically take a longer route that bypasses the city centre.

5 Behavioral urban design

The behavioural model of embodied cognition and enactive problem solving does not only influence the behavioural design of public policies. As we saw earlier in Donald Norman's analysis of behavioural design, the relationship of the human subject to objects and spaces can be represented above all through the concept of affordances. Empty spaces and solid objects such as squares, streets and buildings communicate possibilities of interaction to the subject. These possibilities correspond on a philosophical level to Husserl's "I can" (1969) and on the level of embodied cognition to neuroimaging simulations of possible actions. Whoever designs a city or a house cannot do so in the abstract but must discount the effects of interaction, or in other words of affordances between empty spaces and solid objects and the citizen's neuroimaging perception and simulation.

Behavioural urbanism and its related area of study, behavioural architecture, is an interdisciplinary field focused on the interaction between humans and the built environment, studying the effects of social, cognitive and emotional factors in understanding the spatial behaviour of individuals. The environments we build and inhabit shape our lives and the choices we make. Seemingly arbitrary or irrelevant decisions, such as where to place the kitchen in an office building, have subtle influences on how people who use the building interact. Companies use the same sensors, activity trackers and social networks that are imposed on us as consumers to reroute the habits and behaviours of building occupants. What we are learning is that spaces can be designed to guide us unconsciously ("nudging") towards certain activities, effectively pushing our behaviour in a particular direction. Nudging does not guarantee a behaviour or outcome, it acts more like a reminder (or, in some cases, a warning).

It is cities that provide the everyday context in which people go about their daily lives, and consequently greatly influence their quality of life. A growing strand of behavioural sciences studies the impact of the environment on behaviour of a disparate nature. Recent research, for example, has shed light on some of the mechanisms that lead to an increase in junk food consumption.

Van Rongen et al. (2020) provide us with interesting data that in the Netherlands, there is no direct association between exposure to fast food in the neighbourhood of residence and junk food consumption by residents; rather, exposure to fast food is positively associated with social norms in the neighbourhood. These norms could be descriptive (what most people do) or injunctive (what most people approve of) (*Cialdini et al. 1990*), and it was precisely these norms that were positively associated with the likelihood of food consumption. A study on waste showed how the morphology of our cities can influence our social norms, and how this can in turn influence behaviour. In line with this, several behavioural policy interventions have shown how social proximity can be incorporated through the use of social norms for behavioural change (*Cialdini et al. 2019; Allcott, 2011*). Other studies have highlighted the relationship between how neighbourhoods of residence are designed and behaviours related to physical activity (*Ding et al. 2011*), crime (*Brannan-Smith et al. 2019*), voting behaviour (*Johnson et al. 2004*), attitudes towards residential mobility (*Tjepkema and van Ham, 2009*) and health (*Eben and Turner, 1997; Sampson et al. 2002*).

In cities, the individual interacts with the social context, but it is the city itself that also provides the person with the physical context within which most of his or her life “takes place.” Physical interaction will therefore have an impact on the cognition and behaviour of citizens. The phenomena that arise from this interaction between physical space and social and individual aspects are analysed by disciplines such as cognitive and behavioural architecture (Wadman and Mennis, 1976; Hollander et al., 2020) and environmental psychology (Bell et al., 1997).

Bell et al. (1997) define environmental psychology as the discipline that studies the ways in which characteristics of physical environments influence individuals, groups, communities and social entities (up to entire cultures). At the same time, environmental psychology also studies the ways in which these agents in turn shape physical environments. The theories underpinning environmental psychology are numerous, for the sake of brevity, the main ones will be divided following Muser and Urrutell (2003), distinguishing between two main approaches:

- **Interactionist approach:** includes “analysing the individual’s exposure to environmental stressors in terms of behavioural control and elasticity on the one hand, and environmental cognition on the other” (Muser and Urrutell, 2003). An example of environmental cognition are cognitive maps, i.e., mental representations of an environment (city, neighbourhood, flat, etc.) that the individual creates.
- **Transactional approach:** this approach treats the relationship between man and the environment as a transaction, i.e., something that assumes its own separate existence. This transaction therefore constitutes a unicum, which becomes the object of research. “Environmental psychology is the study of transactions between individuals and their physical context. In these transactions, individuals modify the environment and their behaviour and experiences are modified by the environment” (Gifford, 1997).

Behavioural architecture is a more recent and emerging discipline that aims to incorporate the latest developments in the fields of cognitive neuroscience and evolutionary biology into the development of architecture and urbanism. Wadman and Hollander (2004) identify five dimensions that determine a human’s cognitive reaction to a city:

1. Edges: e.g., of a street or a corridor;
2. Shapes: the representation of objects on a building façade;
3. Patterns: repeated sequences of behaviour;
4. The narrative: emphasising the historical context and the significance of objects in a city;
5. Biophilia: the desire to surround oneself with living beings.

These dimensions are based on notions from neuroscience or biology, in particular how the human brain has evolved over time in ancestral contexts such as the savannah. The theoretical foundations of behavioural architecture thus allow us to scientifically validate hypotheses about how citizens react to urban constructions, both in the laboratory and in the field (Hollander et al., 2020).

Behavioural architecture requires sophisticated insights that cannot come from architects, but from behavioural psychologists. Architects often design buildings without knowing the psychology

of the people who will live in them – or with assumptions about people that are naïve, or totally false.¹¹

6 Behavioral city

The behavioural design of public policies (welfare, mobility, taxation, etc.) and urban design is based on the behavioural and cognitive dimension of the citizen. City public policies decided by the city government have objectives in the public interest and in favour of the citizens’ welfare. To achieve them, they must identify the ways that best match the behavioural expression of the subjects. That is, they must be designed at the behavioural level. They cannot be chosen in the abstract. The same argument must be made about planning the development of a city. Although behavioural design of cities such as behavioural urbanism is a nascent and uncommon approach, it has highlighted the importance of conserving the empty and solid spaces of cities in relation to the possible perceptual, emotional and behavioural effects of citizens. What has been lacking so far is the integration between the two approaches that the Behavioural City concept aims to achieve.

How could the conceptual model of Behavioural City be outlined? According to these four conceptual blocks:

- I. Empty spaces such as squares, parks and streets and solid structures such as public and private buildings, bridges and monuments are perceived and felt on an emotional and cognitive level and stimulate specific interaction behaviour of and between citizens.
 - II. The government of a city and its stakeholders, through forms of political negotiation and administrative decision-making, elaborate public and individual welfare goals that are implemented through different modes of policy making.
 - III. The government of a city and its stakeholders in order to achieve their policy objectives, which generally aim at citizen behavioural change, must design the policy measure in relation to how it is perceived and cognitively represented by the subjects and how this elaboration determines the desired behavioural change.
 - IV. The physical structure of a city, and in particular how it is designed and planned, can be a useful tool for achieving the
11. For example, behavioural psychologists have shown architects to be uncomfortable with mass, particularly neoclassical, that define geometry and axes. Today, the new architect possibility behavioural architecture that was inspired by dissolving the mass played in the building. The valid example is that some human activities place human beings in a similar relationship, for example, in a hotel where it comes to taking guests, eating, sleeping, taking up the room and sleeping etc. The lesson taken is the guest, the service guests are any role of service service staff group, if working together to make the hotel programme can smoothly in the course of a project. The architect had to work systematically on a horizontal and vertical plane. The owner would involve the architect from the very beginning of the project so that some common decisions regarding perceived space and movements can be addressed by the architect while designing the facility.



policy-maker's goals, as it can help bring about the change in citizen behaviour pursued by the city government.

Figure 4 shows how the behavioural sphere of the citizens is the main real reference for the dynamic design of a Behavioral City and how on this basis policy making can interact reciprocally with urban design and planning.

If one wants to illustrate the Behavioral City Cycle recursively, one looks at Figure 5. In this figure, one can see how certain policy-making goals can be achieved, through behavioural insights that highlight the most effective levers for changing behaviour. From this point of view, the urban environment can represent an architecture of choice designed also to stimulate certain behavioural changes. Once this new environment is realized, direct effects and unintended consequences on human behaviour are analysed and, based on the results, feedback is given to policymakers to adjust the focus in a second round of the cycle.

The infrastructure of a city can have a huge impact on people's behaviour, attitudes and habits. How can urban planning improve wellbeing, social cohesion and group identity? Summarizing the most important literature in this field, here are seven behavioural cues for the design of public spaces that can help (Fiduria, 2020; <https://behaviorsforbehavioral-urban-design/>).

1. **Make it accessible.** Understand the physical barriers of your beneficiaries. For example, consider child-friendly facilities to attract more parents, comfortable seating and barrier-free facilities for the elderly to attract large family groups, or improved public transport times to attract more students.
2. **Make it safe.** People avoid situations where they are confronted with uncertainty and discomfort. Plan areas that are protected from the weather and design spaces to provide sufficient levels of privacy (this may differ from one culture to another).
3. **Make it clean by design.** Rubbish and waste smells make public spaces unattractive. Provide a sufficient number of waste bins and make them perceptually salient (by creating amusing

designs of the bins or using salient stickers on the ground), make sure that waste bins are stored at an adequate distance from people (especially during hot weather), or make it a prerequisite for café and restaurant operators to adopt deposit return systems.

4. **Make it social.** People like to gather and interact with each other in focal points. Select these focal points on purpose and adapt them to the preferences of your target group, e.g., by integrating a cafeteria, blue spaces, community buildings or gardens, art-making areas.
5. **Make it local.** Levels of involvement increase with ownership and acceptability. Use participatory planning processes during the prototyping and design phases, involve qualified facilitators with links to the community, or encourage young people to volunteer in site operations and management at an early stage.
6. **Make it fun.** Integrate gaming elements into the design that repeatedly allow interaction between community stakeholders. Classic examples are children's playgrounds, walking trails or table tennis tables; newer, more team-oriented alternatives are health walking competitions or geocaching activities.
7. **Make it usable.** Design the space to be flexible enough to facilitate future community events. For example, think about the possibility of hosting flea markets, outdoor exhibitions, food truck fairs, concerts, festivals or temporary parks.

The above are general behavioural indications for a Behavioral City. Let us now look at some more specific applications to urban public policy.

7 Applications

Various are the applications of the behavioral city concept from the environment, sports, education, culture and tourism, etc. I will now focus only on energy saving, social inclusion, knowledge transfer and mobility.

7.1 Energy saving

This area contains various examples implementing the Behavioral City concept. Various nudges have been introduced in the domestic sphere to promote energy saving. Most (Haler and Sundén, 2006) are based on the mechanism of feedback on our choices in order to generate forms of learning and corrections. Most effective has proved to be the Ambient Orb, a luminescent ball that turns red when consumption is excessive and green when it is acceptable. The introduction of this simple device resulted in energy savings of up to 40%.

One of the most emblematic is the following, which can apply to various public policies such as taxation, health, insurance, etc. As we saw earlier, it is well known that the individual is influenced in his behaviour by what people close to him do, e.g., neighbours and neighbourhood residents. One condition, however, is that there is some form of common experience and frequentation, which may be participation in the neighbourhood committee, in some local association, in some common initiative, such as markets, festivals,



charity, religious, recreational and cultural activities. If there is this dimension of social capital, then it is possible to stimulate citizen behaviour with "social norm nudging" (Thaler and Sunstein, 2008) describing what most people do in their neighbourhood or the prescriptive principles that regulate community life. The success of the UK government's tax compliance letter is based on this principle. The same success occurred with information on electricity or gas consumption that referred to the average of what neighbours consume (Thaler and Sunstein, 2008). We refer, for example, to the work of Schultz et al. (2007) and Allcott and Todd (2014) that used social norms as a tool to stimulate imitation and emulation. They measured the effects of encouraging households to reduce their electricity consumption by sending them letters comparing their energy consumption with that of their neighbours. Another successful mechanism is the Watson display that records our consumption patterns and compares them with those of others. When the comparison takes place mainly with neighbours, feedback together with social imitation become powerful behaviour correctors.

In both cases there was a significant increase in tax compliance and energy saving behaviour. This phenomenon vanishes, however, in urban situations characterized by fragmented housing developments, disconnected from each other without common meeting places where a minimum of social capital and community life can be created. For example, the same social norm nudging for tax compliance tested in some American cities did not yield the same results as in British cities. In this case we are faced with an example of the application of Behavioural City. Behavioural Insight tells us

that if we want to stimulate people to consume less electricity and gas we can use social norm nudging as long as the city is designed to generate social capital and community neighbourhood among the city's inhabitants. Behavioural urban design must therefore direct the development of cities to foster this phenomenon of social and emotional contiguity and collaboration, and must avoid building atomic neighbourhoods in which social relations are rarefied and atomistic. In this way, city public policies will be able to stimulate behavioural change in citizens by leveraging the social norm nudging of the example or norms of other neighbourhood inhabitants.

7.2 Inclusion and social space

One of the best known concepts on the perception of space is Lefebvre's spatial triad and Soja's "third space". Soja (2003) suggests that space should not be approached in a binary way, but as a middle ground between material and mental space, so space is both real and imagined.¹² This is why the social and individual perception of space is closely related to the injustices and inequalities that

¹² Soja's theory of "Thirdspace" (2003) uses three Latin adverbs: *Primumspace* (Somewhere), *Utopiaspace* (Nowhere), and *Thirdspace*. *Primumspace* is the physical, built environment, which can be mapped, literally measured and "seen" in the real world. It is the product of planning, laws, political decisions and which change over time. *Somewhere* is collective

spaces produce (Borch, 2017). We must recognise that places are no longer only spatially delimited, but are instead defined by the interactions of different cultures and multiple identities within and beyond static space (Mauzy et al., 1995). When people use a public space, it becomes a process of transforming a constructed form into a meaningful place with collective meanings and a mixture of identities. An inclusive public space should allow people to feel physically and psychologically included; therefore, being in a public space is both a physical and emotional experience. Public spaces are an integral part of our urban environment. Research has established that public spaces are perceived as beneficial for both environmental and social sustainability, for economic development, for promoting positive health outcomes and for building a stronger sense of community within neighbourhoods. Public spaces can also have a positive impact on social wellbeing and improve community resilience by shaping people's perceptions of social connectedness, trust, welcome and safety. In general, an inclusive public space is often understood as a "public space for all". It suggests that everyone should feel welcome, included and not discriminated against on the basis of gender, age, sexuality, race, ethnicity, religion, cultural background, socioeconomic status and/or personal values when in a space. Public spaces are not always designed and managed with inclusivity in mind, so not everyone gets the same result and benefits from using it. For example, a public space may be physically designed to be accessible and welcoming for all, but if the space is dominated by a certain group of people, then that space becomes socially and emotionally exclusive for others who do not feel able to identify with that dominant user group. This is also why the inclusiveness of public space is difficult to assess, because it is influenced by both the tangible physical environment and the intangible psychological experience, in combination with other factors such as historical process and neighbourhood context. Sometimes what seems ideal and welcoming for a specific group may be emotionally alienating for others (Rishbeth, 2005).¹² The governance of public space must guarantee the rights of marginalised groups. Creating spaces that allow for freedom of expression, whether through art, protest, festivals, parades, versatility in activities or simply the expression of human empathy, could improve the inclusion of different marginalised or vulnerable groups, as well as protect

the city's multicultural environment (Oulah H-Dm and Athas El-Zohary, 2018).

Default options could also be incorporated into the urban architectural structure itself to promote inclusion. One could conceive of architectures that correspond to the passive and inertial tendency of the citizen, thus favouring the objective of social inclusion. Urban planner could design quasi-automatic walking routes leading to public spaces, such as squares or multi-purpose cultural areas, attractive from the point of view of services, where one could participate to collective initiatives of ethnic and social inclusion. Neighbourhoods that are designed to increase the interaction of their inhabitants and which in this way can develop forms of aggregation and social capital¹³ are the most suitable spaces for developing processes of integration and social inclusion. In this type of neighbourhood, when necessary, the policymakers can also use social norm nudging to promote greater inclusion behaviours.

7.3 Knowledge transfer

The knowledge economy has as its main focus the generation of knowledge within academic and research institutions and its transfer and contamination towards the business world. A Behavioral Insight that may emerge from the increasing generalisation and complexity of knowledge involved in innovation is the importance of face-to-face interaction and proximity between universities and companies (Viale, 2011b; Cusumano et al., 2014). The need for proximity has been emphasised in recent studies (Arundel and Gassma, 2004) for an explanation according to complexity theory (see Viale and Pizzelli, 2010; Viale, 2011). Virtual clusters and metadistricts cannot play the same role in innovation. Proximity and face-to-face interaction are not only important to minimise the bottleneck in the transfer of tacit aspects of technological knowledge, but face-to-face interaction is also crucial for collaboration because of its positive linguistic and

space = how that space is conceived in the minds of the people who inhabit it. It is a product of (re)writing strategies (re-writing and social norms that determine how people might act or behave in that space). Distinction (ii) "real and imagined" space (Jardí Horta, 1996) says that people actually live in a big experience that shapes space. This function in the real space (distinction iii) is tracked through the experiences of the second-order.

12. Some authors argue that public spaces are increasingly commodified, particularly by commercial activities and socially privileged people who seem to avoid conflicts and public space (Harms, 2000). This is when that socially privileged people have a greater impact on the planning process of public spaces. For example, some argue that contemporary public spaces in North America are created primarily by the white middle class while marginalising other ethnic groups and people of lower socioeconomic status (McCann and Raco, 2005).

13. One of the conditions favouring the development of a strong network of exchanges and relationships between contracting members. The social capital that is created, representing something by the government's public policies, is able to contribute to the social functioning by processes of economic development and social integration in marginal areas. There are different factors that can generate social capital. Differing between social and the same-density (social, cultural, religious, economic, etc.) are certainly the most relevant. But how can we multiply the identity when there are problems of inclusion? Starting through the creation of a social or local identity (or of mutual obligation and trust), other (local) is possible and emerges from, such as the recognition of a problem within the community, the implementation of initiatives as a project a part of the community, the spreading of local and reciprocal, etc. When the member or part of the community receive a gift they will feel obliged to reciprocate in some way, contributing, for example, to common projects for economic and social development. From this point of view, a local government can promote territorial development with a strengthening of social capital through the stimulation of mechanisms of inclusion and exchange and at the same time the birth of projects of a social nature achieved through jointly between state and community (Viale, 2010a).

pragmatic effect on understanding. It also improves the rate of trust, as neoneconomics has shown (Camerer et al., 2003). Proximity can also increase the respective permeability of different social values and operational norms between academic and industrial research (Viale, 2013). From this point of view, cities and universities could foster the emergence of open spaces for discussion and confrontation, suitable architectures of choice where the behaviour of academics, entrepreneurs and investors is driven to develop a kind of creative interaction, learning to know each other and finally collaborate. These meeting spots must be ergonomically designed on a cognitive level to also foster the entrepreneurial propensity of academic researchers and the confidence-building of investors. As is well known (Viale, 2016; Carchiari et al., 2024) from studies on entrepreneurial behaviour and nudging mechanisms for the creation of new ventures, one of the main problems for those who create a start-up is the critical confrontation with experts who can assess the financial and organisational feasibility of the venture and above all the attractiveness of the new product. In general, various biases characterise the start-up entrepreneur, ranging from overconfidence, overoptimism, illusion of control and motivated reasoning. These biases have an adaptive function to initially motivate the start-up promoters. For a realistic assessment of the product's market feasibility, however, it is necessary to neutralise them to some extent through comparison with market samples and financial, technological and organisational experts. There are proposals aimed at enhancing adaptive controls in the process of creating and strengthening a start-up. The "Lean Methodology" of Roca (2011) is one such proposal: it is characterised by the principles of simplicity, speed and feedback (an example of reactive problem solving). The methodology prescribes the simulation of demand through the input of potential customers and the use of devil's advocates to critically check possible flaws in the production design. After these inputs the start-upper should revise their assumptions and start the recursive control cycle again by testing the redesigned offers and making further small adjustments (iterations) or more substantial adjustments (pivots) to the ideas that do not work. To realise these steps, it is necessary to design ergonomic urban spaces that allow this type of interaction.

In addition, the proximity between researchers, entrepreneurs and investors allows for better interaction between companies and different academic areas of expertise. Indeed, only the university has the potential to cope with the increasing complexity and interdisciplinary nature of new ways of generating innovation. Emerging and converging technologies (e.g., nanotechnology, biotechnology, informatics, Artificial Intelligence, robotics) require a growing division of skilled labour, encompassing the entire knowledge chain from pure and basic research to development. Only a company that can interact and rely on the tangible and intangible facilities of a research university can find suitable commercial solutions in the era of hybrid technological innovation.

Another example of knowledge places where the behavioural approach can play an important role is the Residence Hall where students can be "nudged" towards the university's institutional goals. The optimal living experience lies at the intersection of people, processes and places. The experiences students have in residences contribute significantly to so many areas of their academic careers. The place of residence affects what they learn, the friends they meet, the development of their identity, as well as their overall satisfaction

with university and the likelihood of persisting until graduation. Common goals of student housing projects should include:

- Positively impacting the academic experience
- Promoting contamination from different subject areas
- Presenting oneself to investors and companies
- Improving interdisciplinary collaboration
- Stimulating free discussion and creative experimentation
- Improving the sense of community
- Improving the safety and security of students
- Better serve students of all abilities and skill levels
- Encouraging desired behaviour (e.g., involvement in social activities)
- Improving mental health

In most cases, institutions try to address these objectives by addressing "people" and "processes". However, the third and equally important "P" is "place", and it is often underestimated in the role it plays or left out of the design altogether. By neglecting the powerful role place plays in supporting student accommodation goals, we actually run the risk of impeding progress in achieving an institution's goals. Many industries have found that spaces can be designed to produce specific performance outcomes such as productivity or increased innovation. Similarly, the physical design features of a student housing building can create or limit opportunities for student interaction, making expected behaviours less likely.

7.4 Mobility

Mobility is an area very rich in opportunities for the expression of the behavioural city. One thinks, for example, of road safety (German Society, 2023). The way a city is designed and the road surface can be a conductor or not of drivers' attentional deficits. One of the functions of nudges is precisely to neutralise attentional errors (Thaler and Sunstein, 2008). From forgetting the petrol cap after a refuelling to forgetting the credit card at an ATM after a withdrawal, various forgetfulnesses characterise our daily lives. Behavioural sciences can help us neutralise errors or at least make them reversible or venial. In road safety there are many behavioural applications to the way cities and streets are designed. Buildings, empty spaces and streets are able to communicate affordances on how to interact with them. From these affordances derive crucial safety aspects. Road safety indicators are precisely aimed at measuring whether a road is well designed and placed.

Think of the blind spots in the city: from the nooks and crannies of certain side streets to the crossroads that suddenly end up against a wall, in a meadow or a ditch. It is not necessarily only a fixed place. The blind spot can also "move", depending on how a lorry or any other means of transport moves. And if this area is mobile at every turn, it is obviously even more dangerous. There are thousands of blind spots in a big city, all equally at risk of accidents. We are referring to every junction without traffic lights, those simply provided with a stop sign and punctually occupied by vehicles parked right up to the "corner", which in this way prevent the oncoming traffic from seeing who has right of way. The 6-metre rule, the distance from the junction within which it was once forbidden to park, precisely so as not to obstruct the view to the left and right,

has in fact been abolished: today people push up to the last useful centimeter and even further, literally blinding drivers about to cross the junction. Accidents due to this silent suppression of the rule are daily, serious and widespread.

According to [Hartshorn, Bailie and Jones \(2005\)](#), the effect of traffic on the public sphere is difficult to overestimate. In many US cities, more than 70 per cent of urban space is made up of roads and car parks. Even in the UK, 30%–40% of public space is the responsibility of the traffic engineer. Yet these professionals receive no training in urban design and usually place little value on creating good quality places, preferring instead to focus on optimising traffic capacity and safety. Recent experiments in continental Europe and more recently in the UK have found that removing the traditional separation of traffic and people in urban areas can make streets safer and less congested. The removal of kerbs, barriers, road signs and standard road markings forces motorists to use eye contact with other road users and pedestrians. The result is slower and more careful traffic, greater safety for cyclists and pedestrians, and an overall more attractive urban environment in which local architecture and culture prevail over standard road infrastructure ([Hartshorn, Bailie and Jones, 2005](#)).

Nowadays, intuitive design principles that suggest to users how to reliably use their mobile phone or tablet without further instructions are very common. Similarly, a self-explanatory road design should be as intuitive as possible for the road user, so that danger symbols, prohibition and prescription signs are no longer necessary in the human-road interface. Therefore, it is not only important to build a clear system of road categories to inform the driver of the appropriate speed or to set speed limits, Road General should also provide a clear impression of how to drive and should pre-programme driver expectations so that the driver is never surprised or encouraged to take any risks. A German manual on road safety ([PIARC, 2019](#)) analysed about 1,400 accidents in Germany. In this manual, the most important errors that violate the principles of self-explanatory road design are presented. Three human factors were analysed, which are key requirements for self-explanatory design (reference will be made to [PIARC, 2019](#)):

The first is to give road users sufficient time. The time it takes an average driver to adapt from one traffic situation to the next or to adjust to new demands is much longer than many current guidelines indicate. Since human beings are not constantly alert and searching for new information, they need more time. A user-friendly road will give drivers the time they need to adapt to new and unsuspected situations.

The second: a road must offer a safe field of vision. Dull, blurred, misleading or distracting impressions affect the quality of driving. The road, together with the surrounding field, offers an integrated field of vision. This can stabilise or destabilise drivers; it can tire or stimulate them. It can also lead to an increase or decrease in speed. Speed, lane keeping and directional reliability are functions of the quality of the field of vision.

The most interesting behavioural requirement is the third: the road environment must correspond to the cognitive and perceptual models of road users. Drivers follow the road with expectations and orientation patterns formed by their recent experience and perceptions. These influence their perception and actual reactions while driving. The same principle applies when climbing stairs. After only a few steps, the balance of movement adapts to the newly

performed sequence of steps. In most cases, this is a subconscious process. However, if a step has a different height, the balance of movement will become disordered – with the possibility of tripping or falling. Similarly, the adjustment of the driving programme on the road takes place in the subconscious. The perception of the lane, the edge and periphery of the lane produces a general impression and generates sense-motor body stimulation effects. Drivers react to these elements of the road with their actions, in the same way as someone climbing stairs reacts intuitively to the height, depth and width of steps. Unexpected objects disturb the automatic sequence of operations, possibly causing the driver to “stumble”. After several critical seconds, the disturbance can be managed. Therefore, planners and designers must try to keep the characteristics of the road in a logical sequence. They should introduce unavoidable changes as early and clearly as possible and exclude any sudden changes that might confuse the driver.

To convince drivers to reduce speed, several effective behavioural design tips have been implemented worldwide ([Thaler and Sunstein, 2008](#), my reference is to [Pietroni and De Rosa, 2021](#)). There are experiments with nudges using optical illusions. A prime example is to paint horizontal lines on motorway asphalt that become progressively narrower. These lines amplify the feeling of speeding among drivers and create a moment of surprise in the driver's routine. Drivers perceive the situation as if they were speeding and react intuitively by slowing down. The same effect can be purposely replicated by using a “noise nudge” (different coating tapes) on the asphalt can considerably increase the internal noise level at a given speed. Since people do not like noise, they are urged to slow down to feel more comfortable. At the curve between Lake Shore Drive and Oak Street in Chicago, a series of horizontal white stripes have been painted on the road, which become progressively narrower as drivers approach the sharpest point of the curve, giving them the illusion of acceleration and prompting them to tap on the brakes. According to an analysis conducted by the city's traffic engineers, 36 per cent fewer accidents occurred in the 6 months after the lines were painted than in the same 6-month period the year before. Similar behavioural design measures are now being applied in China and Israel to limit speeding.

In another experiment conducted in the UK by Norfolk County Council, more than 200 trees were planted on access roads in north Norfolk that had a history of speeding problems. The results found that drivers reduced their speed by an average of two miles per hour. Again, as the car approached the village, the trees, planted closer and closer together, gave the impression that the vehicle was moving faster. This encouraged motorists to slow down.

In another experiment in the US, the Virginia Department of Transportation painted white zigzag signs instead of the familiar dotted straight lines to warn drivers approaching road intersections used by pedestrians and cyclists. They found that the zigzag signs slowed the average speed of vehicles and increased drivers' awareness of pedestrians and cyclists. They also noticed that the effects of the behavioural design did not wear off once motorists got used to it, but still slowed down a year after installation.

Building infrastructure such as traffic signals does not mean that people will always follow them. Behavioural suggestions, such as displaying the seconds remaining before the traffic light turns green, are likely to reduce the number of people who do not

respect the signal. Such behavioural design takes into account the fact that people are usually in a hurry. Behavioural designs can be applied to pedestrian crossings at traffic signal crossings. At road crossings there are often two signals in sight: one positioned immediately after the zebra crossing and the second signal on the other side of the crossing once it has been crossed. This causes drivers to continue moving slowly, without stopping at the zebra crossing and thus preventing pedestrians from crossing. Therefore, to stop cars at zebra crossings, it is preferable to place only one traffic signal just before the beginning of the zebra crossing, so that drivers are prompted to focus their attention on the one traffic signal.

An interesting approach to mobility is provided by what is called “ruling by removing rules” (Loose and Morina, 2020; Loose and Morina, 2022). The goal is to change the behaviour by removing certain rules. For example, the removal of some road signs and road markings may increase drivers’ responsibility and awareness. In fact, an excess of road signals decreases the drivers’ responsibility and attention from the road and from the other users. On the contrary, a reduction in signage obliges drivers to pay better attention to other drivers and pedestrians.¹⁵

The other chapter on mobility relates to its sustainability. Sustainable mobility is a key area in the application of the behavioural city policy making approach. There are various expressions of a prescriptive behavioural city model in this context. Many of these exploit the attributes of judging summarised in the acronym BEAST (Thaler and Freytag, 2022). Interventions must be Funny, Easy, Attractive, Social and Timely. Various interventions over the years have fulfilled the attributes of this acronym. Funny as in the audible underground steps in some Swedish cities, Easy as in simplified routes to switch from one public transport to another, Attractive as in the use of sensory and perceptual stimuli (light, sound and smell) in some railway and underground stations, Social such as the use of “desire paths,” small walking paths created by the spontaneous passage of passers-by,¹⁶ or some campuses to trace the walking routes of students, Timely such as the timeliness of messages the citizen should receive on alternatives to car transport.

For a comparative account of behavioural initiatives on sustainable mobility, see Paterni and De Luca (2023) and the Herbert Simon Society study for IEEL ANCI (2024). I will give just one paradigmatic example from Herbert Simon Society (2024).¹⁷ In

2015, the “Year of Walking” was declared in Vienna. Throughout the year, various events on the habit of walking were organised targeting different population groups. The aim of the campaign was to present walking as a modern, effective and healthy mode of transport. To encourage the practice, activities were presented to the inhabitants to add variety to the walking routes, exploratory walks were offered and prizes were awarded to participants. In order to reach as many people as possible, two products were presented at the beginning of the campaign: a map of walking routes and the “Walking Vienna” app (Wien zu Fuß App). The map indicated the most interesting walking routes, green areas, drinking fountains, shoe shops, markets and shoe shops. The “Vienna on Foot” app, which is currently still in operation, implemented a walking trip planning system capable of identifying three types of routes: fast routes, green routes and tourist routes. The app also used gamification elements. There were two initiatives to organise group trips: the walking calendar and the walking café. The Year of Walking concluded with the “urban village.” The 3-day event was held in the square in front of Vienna City Hall where a huge map of the city was placed. Participants received pens and were able to trace their favourite routes. At the end of the initiative, 49.9 per cent of the respondents said that there were enough walkable routes in Vienna, compared to 43.7 per cent of those who agreed with this statement before the campaign.

To further stimulate the take-up of the Year of Walking events, the SWITCH campaign was organised. This aimed to change the mobility behaviour of citizens from using cars to walking. SWITCH was created within the Intelligent Energy Europe (IEE) programme managed by the European Commission and used behavioural change approaches to encourage users to use active modes of travel rather than the car in the context of short trips. The innovativeness of this campaign stemmed from the combination of Personalized Travel Planning (PTP) with professional arguments regarding health benefits and forms of gamification. The PTP was based on personalised messages with respect to the users in order to close information gaps and overcome behavioural barriers. In order to further improve the effectiveness of the tool, it was complemented by various information and communication technologies that made it possible to implement gamification features and to create messages that were customised with respect to their content and timing. SWITCH targeted people who had recently been involved in a move or who had recently received medical advice regarding the importance and benefits of physical activity. SWITCH targeted three easily influential groups of people who regularly used a car but were also interested in healthier mobility alternatives. During the collection of the material, particular attention was paid to instigating information about mobility, the health benefits of physical activity and recommended practices. These items were also categorised according to the characteristics of the individuals (students, elderly, parents, etc.) to whom they were subsequently addressed. Finally, to further incentivise participation in the campaign, a lottery was organised involving all participants. The study found that campaign participants increased the number of their walking trips by 4%. This resulted in an increase of approximately 47 h per week dedicated to walking. Part of the success of the campaign was due to the strong collaboration with local stakeholders and participants who provided important feedback regarding their personalised mobility experience.

15. An interesting observation by the Dutch traffic engineer Hans Moederma reported by van Buijten (2016) concerning the absence of green traffic lights: “When you look outside the window, they’ll never be there.”

16. “The path usually represents the shortest or most easily followed route, although an origin and a destination, and the breadth and depth of its surface extend to various dimensions of the level of traffic to which it is dedicated. Many of these typically emerge as community structures, compared to more deliberately constructed routes that are single and more structured. Once a path has been recognised, the cultural vegetation, subsequent works tend to follow that path, because it is then convenient that a new path created by themselves.”

17. The case studies in the report are analysed by Guendel Carliana.

The example of Vienna shows the importance of the city model in promoting behavioural change towards sustainable mobility and a healthy lifestyle. The acronym PEAST also applies in full here. A city must be designed and planned to allow a funny, easy and attractive switch from private to public transport or better still to walking or cycling. The social dimension generates emulative contamination and the herd effect. An initiative like this must be timely in sending out personalised messages. Conversely, in a city without the cultural stimulation, attractiveness and street organisation of Vienna it would be much more difficult to develop nudges for sustainable mobility.

8 Conclusion

How to implement a Behavioral City? The article is focused on the new conceptual model of Behavioral City. However, it does not show any satisfactory and complete real-world applications. Actually there are not yet clear case studies in which Behavioral City concept might refer to. In any case the practical pathway in implementation should rely in the following series of steps:

- 1) Participatory government assessment with civil society and economic stakeholders to choose policy objectives. The Behavioral City concept envisages the bottom-up participation of civil society, key stakeholders together with government in the definition of urban planning with regard to public policy objectives and the choice of behavioural instruments to implement them.
- 2) Behavioral insights to choose policy instruments. The policy-making objectives of city government should be realized through the choice of the most effective means. To achieve this, they should be identified through a behaviourally-tested selection. Ultimately it is an experimental Behavioral Insight exercise (preferably through Randomized Control Trials or through surveys or field studies and if neither of these tools is possible through laboratory experiments) aimed at comparing the effectiveness of different tools such as nudging, boosting,¹⁸ BRAN,¹⁹ traditional public communication, economic incentives, regulation or modifying

citizen behaviour in order to achieve city government policy objectives.

- 3) Mixed working groups of urban planners, architects, behavioural scientists, behavioural economists, and public policy experts to assess how urban planning can incorporate these tools. After experimentally identifying the best policy tool to achieve government objectives, the next step is to understand how this tool can be expressed and amplified by urban design choices. In particular, this will be the case if solutions have been selected in which the affordances of the urban structure can generate behavioural effects consistent with policy goals.
- 4) Empirical tests and VR simulations of the behavioural effects of urban layouts. To test the behavioural effect of the design of the physical urban structure, one can employ Virtual Reality simulations or, when possible, refer by analogy to urban design initiatives implemented in other urban realities. In this case, behavioural effects can also be investigated through empirical methods such as surveys or participant observation.
- 5) Participatory evaluation with civil society and economic stakeholders to choose the behavioral city solutions to be preferred. The final choice of the urban solution that has behavioural effects on people towards policy goals can be achieved through forms of democratic participation such as online polls or actual referendums and votes or public discourse.
- 6) Metrics for ex-post impact assessment of proposals. For the measurement of behavioural effects by urban design, quantitative measures that show a change from historical data should be introduced. This longitudinal approach should be able to describe the presence of a positive, negative or no effect on behavioural factors such as waste collection, energy consumption, sustainable mobility, social inclusion, etc.

There are various difficulties in the implementation of the behavioral city model. The main one is the reluctance with which city policymakers realize the usefulness of the behavioural approach to public policies. Generally in policy making in continental Europe the legal formalist approach prevails together with political and electoral priorities and budget constraints. In this way the design of cities and public policies is often realized without questioning their real impact on the wellbeing of the citizen. On the other hand, the Behavioral City approach, in addition to leading to greater effectiveness in achieving public policy objectives, would also allow the exploitation of urban design for behavioral purposes in order to make public policies more efficient.

In conclusion, the behavioral city model aims at enhancing the role of behavioural sciences, finally used in public policy design on the one hand and in urban design on the other, towards their function as a bridge between public policies and urban planning. Or in other words, on the basis of the behavioural tools identified in policy making, the aim is to shape the affordances of the city's physical structure in such a way as to create new architectures of choice capable of orienting the citizen in the direction desired by policymakers.

18. The goal of the behavioral approach to justice (BACJ) (introduced by Gershoff and Hersh (2018) among with Gershoff (2017), Shalvi and Gershoff (2020)) is called BACJ. The aim of the BACJ is to continuously improve the decision-making with already present in justice to be introduced new ones.

19. Behavioral Finance Adaptive Nudges (BRAN) make available to citizens options and target ways to choose that are useful in specific situations, governments and that in this way strengthen their autonomous ability for personal making and success in the performance of a task (Vale 2020a; Vale 2020b; Vale 2021). Fraud traps include mainly financial decision-making (avoiding temptation by experts, laudably and a similar fall and huge loss (FF)) that undermines the base line but requires the requirements required during crises an whether or not to accept a solution based on the reason of a time.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RW: Writing—original draft, Writing—review and editing.

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References

- Allison, W. (2011). Social norms and energy conservation. *J. Public Econ.* 95, 91–101. doi:10.1016/j.jpubeco.2011.07.002
- Allison, W., and Todd, B. (2018). The short-run and long-run effects of behavioral interventions: experimental evidence from energy conservation. *Am. Econ. Rev.* 108, 903–937. doi:10.3386/w24000
- Arnsperth, A., and Gertler, A. (2009). Persuasion and the use of public science by innovative transport firms. *Trans. Information New Technol.* 13, 538–560. doi:10.1080/1044759090326024111
- Baltesa (2020). Behavioral insights for city planners and architects. Available at: <https://baltesa.de/behavioral-urban-design/>.
- Bell, P. A., Hamilton, S., Rajaratna, D., and Jankowsky, A. (2017). "Environmental psychology: evolution and current status" in *State of mind: American and post-war perspectives on contemporary issues in psychology* (New York: Oxford University Press), 324–390.
- Björk, C. (2012). *The politics of words: an alternative history of lexicology*. Cambridge: Cambridge University Press.
- Boutin-Smith, I., Suberland, A., and Jackson, J. (2015). "The role of neighborhood in shaping values and perceptions of values" in *Neighborhood effects in neighborhood food problems: a policy context*. Editor B. Manley (Basingstoke: Springer).
- Carmona, C., Loomer, G., and Peltier, G. (2004). Homo-economic, how appropriate can behavior economics? *J. Econ. Literature* 42, 111–144. doi:10.1257/00222510428000000000000000000000
- Chomsky, A. (2009). *Radical embodied cognition science*. Cambridge, MA: MIT Press.
- Clark, R. A. (2007). *Reformer science and practice*. 4th ed. MA: Allyn & Bacon.
- Clark, R. A., Freeman, L. J., Sagami, B. I., Barish, D. W., Bivash, R., and Wynn, B. L. (2006). Managing social norms for persuasive impact. *Sci. Sign.* 1, 1–7. doi:10.1126/scisign.1100000000000000
- Clark, R. A., and Goldstein, N. J. (2004). Social influence, compliance and conformity. *Annu. Rev. Psychol.* 55, 591–621. doi:10.1146/annurev.psych.05.090302.142005
- Clark, R. A., Jones, R. B., and Kellogg, C. A. (1990). A factor theory of normative conflict: recycling the concept of norms to reduce littering in public places. *J. Personality Soc. Psychol.* 58, 101–115. doi:10.1037/0022-3514.58.1.101
- Chen, H. (1977). *Behavioral architecture: toward an environmental design process*. New York: John Wiley & Sons.
- Cohen, B. L. (2014). *The feeling body: affective science meets the creative mind*. Cambridge, MA: MIT Press.
- Crociere, V., Soderstrom, C., and Vale, R. (2020). Behavioral typology as adaptive and non-adaptive frame in entrepreneurial business decision making. *Typo-fiche*.
- Cziszewski, M., Zepke, H., and Straus, H. (2010). Social norm-matching and preferences for household recycling. *Environ. Design Econ.* 18, 101–113. doi:10.1016/j.environ.2010.07.004
- Damasio, A. (1994). *Descartes' error*. New York: Avon.
- Ding, D., Sallis, J. F., Kerr, L., Lee, E., and Rosenberg, D. E. (2011). Neighborhood environment and physical activity among adults. *Am. J. Prev. Med.* 51, 642–652. doi:10.1016/j.amepre.2011.08.009
- DuBois, E. A. (2007). *Antagonism, adaptivity, teleology, agency*. *Phenomenology Cognitive Sci.* 6, 429–452. doi:10.1007/s10992-007-9092-z
- Ellis, L. D., and Turner, M. A. (1987). Does neighborhood matter? Assessing recent evidence. *Urban Policy* 18, 411–494. doi:10.1080/03011418708839522000
- Ellis, J. (2019). *Urbans and the mind*. Cambridge: Cambridge University Press.
- European Commission (2006). Road safety: new European rules on seat belt use. Available at: http://ec.europa.eu/transport/press-release_2006_003_en.htm (Accessed September 30, 2016).
- European Union (2016). Behavioral insights applied to policy. *European Report* 2016.
- Festinger, L., and van Marck, W. (2009). Neighborhood change. *Personality Matter Urban Stud.* 46, 2103–2127. doi:10.1016/j.jurman.2009.03.001
- Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford, CA: Stanford University Press.
- Gallagher, J. (2014). "Environmental psychology and embodied cognition" in *The ecological handbook of embodied cognition*. Editor L. Shapiro (London: Routledge).
- Gallagher, J. (2017). "Embodied teleodynamics" in *Activating the mind*. Oxford: Oxford University Press.
- Gallagher, V., and Ogburn, E. (1994). Mirror neurons and the simulation theory of mind-reading. *Trends Cognit. Sci.* 12, 401–403. doi:10.1016/1044-5465(94)90020-7
- Gallagher, V., Kippen, C., and Boudreau, H. (2004). A unitary view of the basis of social cognition. *Trends Cognit. Sci.* 8, 416–422. doi:10.1016/j.tics.2004.07.002
- Gallagher, V., Malmgren, A., Boudreau, H., and Vale, R. (2021). "Embodied embodied teleology" in *Ecological handbook on embodied teleology*. Editor R. Vale (London: Routledge).
- Gibson, J. J. (1977). *The perception of the visual world*. Boston: Houghton Mifflin.
- Gibson, J. J. (1978). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
- Gibson, J. (1977). *Environmental psychology*. Boston, MA: Allyn & Bacon.
- Gigerenzer, G. (2012). *Embodied heuristics*. *Front. Psychol.* 3, 713. doi:10.3389/fpsyg.2012.00713
- Gigerenzer, G., and Gerdeman, S. (2011). Rational decision making. *Annu. Rev. Psychol.* 62, 431–452.
- Gigerenzer, G., Todd, P. M., and The ABC Research Group (1999). *Simple heuristics that make us smart*. New York, NY: Oxford University Press.
- Goldman, R. L., Clark, R., and Goldstein, N. (2008). A room with a conscience: using social norms to motivate environmental conservation in hotels. *J. Consumer Res.* 35, 472–482. doi:10.1086/588810
- Groth-Satoh, E., and Festinger, L. (2010). Judge versus juror: how different are justice and theory? *Acad. Manag.* 25, 140–163. doi:10.1007/s12225-010-9163-0

- Wilkinson, M., and Kellman, F. (2020). *Behavioral insight*; Cambridge, Mass: The MIT Press.
- Wojcik, R. (2010). *Behavioral insight: How small changes can make big differences*; New York, NY: Random House.
- Worthington, K., and Jones, P. (2015). Improving traffic behaviour and safety through urban design. *Proc. R. Soc. Civ. Eng.* 138, 34–41. Pages 14014. doi:10.1080/13633685.2015.1065334
- Harvey, D. (2006). *New Urbanism as creative destruction*. *Geogr. Ann.* 88, 3. doi:10.1111/j.1468-0459.2006.00211.x
- Yokel, J. (1998). *The psychology of interpersonal violence*. New York: Taylor.
- Walsh Street Society (2022). "Le scopie comportamentali per il miglioramento della sicurezza stradale." in *Appunti di Ricerca per il Design*: 300.
- Walsh Street Society (2024). Behavioral insights per la mobilità. *Guida essenziale per le autorità pubbliche*. Available at: <https://www.walshstreet.org.uk/wp-content/uploads/2024/01/Behavioral-Insights-Guide.pdf>
- Worthington, K., and Groom-Jones, T. (2017). Nudging and boosting: meeting or improving good decisions. *Respect. Psychol. Sci.* 12, 973–988. doi:10.1177/1745691617702494
- Worthington, K., and Groom-Jones, T. (2020). "Boosting and nudging: two paths toward better behavioral decisions." in *Practical education and real behavior*. Editor B. Viale, U. Fiboni, B. Almondi, and S. Stranisci. (Cheltenham, U.K.).
- Worthington, K., and Horning, M. S. (2019). Fast and legal: heuristic tests of social rationality. *Soc. Cogn.* 37 (1), 563–588. doi:10.1177/0956797618800734
- Worthington, K., and Horning, M. (2015). ABC research group: social heuristics that make us smart. New York: University Press.
- Yokel, J., Pridle, J., Loring, A., Lynch, L., Brown, J., Hefin, L., Jacob, R., et al. (2020). Cognitive responses to urban environments: behavioral responses to job and field conditions. *Urban Des. Int.* 26 (4), 236–271. doi:10.1080/13602041.2020.1811220
- Yokel, J., and Shallice, T. (2019). How effective is nudging? A quantitative review of the effects and limits of empirical nudging studies. *J. Behav. Exp. Econ.* 86, 47–64. doi:10.1016/j.jbe.2019.05.005
- Yonck, E. (1989). *Man perceiving: is a pure phenomenology and is a phenomenological philosophy second look: studies in the phenomenology of constitution*. Dordrecht: Kluwer Academic.
- Yonck, E. (2009). "Muttering people." in *The new science of how we control our cities*. New York: Farrar, Straus and Giroux.
- Yonck, E., Pappas, C., Rogers, A., Tucker, A., Rubin, A., and Jones, K. (2015). Spatial scale and the neighborhood effect: multilevel models of voting at two recent British general elections. *Am. J. Political Sci.* 59 (3), 345–354. doi:10.1111/ajps.12345
- Yonck, E. (2011). *Thinking fast and slow*. New York: Farrar, Straus and Giroux.
- Yonck, E., and Jones, K. (2018). Nudging without rules: not only nudges. *Regulation*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/734568/Regulation-Without-Rules.pdf
- Yonck, E., and Jones, K. (2022). Rule-free regulation: exploring regulation without rules and after 2019. *Thematic Comments*. *J. Theory Soc. Behav.* 52 (1), 22–34. doi:10.1111/jtsb.12299
- Yonck, E., Harris, E., Yonck, T. D., Wagonmakers, E. J., and Harris, A. J. L. (2021). No evidence for nudging after relaxing the pollution ban. *PLoS One* 16 (1), e0238881. doi:10.1371/journal.pone.0238881
- Yonck, E. S., Arango, J., Grooms, H., Emerson, A., Pellegrini, A., and Taylor, J. E. (2018). Benefits of international migration: a review and appraisal. *Popul. Dev. Rev.* 48 (4), 431–468. doi:10.2307/2388462
- McKen, E., and Black, J. (1999). Private and public space: communicating London to the UK City. *Antipode* 31 (3), 364–381.
- Michon, P. (1985). *The phenomenology of perception: urban highways*. New York: The University Press.
- Michon, P., van Hater, M. M., and Wille, B. (2011). The behaviour change wheel: a new method for characterizing and designing behaviour change interventions. *Implement. Sci.* 6, 42. doi:10.1186/1745-6215-6-42
- Michon, P., and Vassil, H. (2015). "Environmental psychology: Part II: how to social psychology (Meyer)." Available at: <https://www.michon.org.uk/teaching/EnvironmentalPsychology/PartII/HowtoSocialPsychology.pdf>
- Nelson, A., De Bruin, L., and Gallagher, S. (2010). *The Oxford handbook of cognitive*. Oxford: University Press.
- Nelson, D. (1991). *The design of everyday things*. New York: Basic Books.
- Oliver, A. (2017). *The urban landscape and public policy*. Cambridge University Press.
- Oliver, A. J., and Nee, S. (2010). A quantitative account of social and moral consciousness. *Behav. Brain Res.* 24 (2), 99–107. doi:10.1016/j.bbr.2010.01.011
- Open (World Road Association) (2019). Road safety manual: A manual for practitioners and decision makers on implementing safe system infrastructure. Available at: <https://www.worldroad.org/eng/PlanningDesign/OperativeDesigningRoadUsers/DesigningSafeBehaviour>
- Parikh, P., and M. (2010). *Le nuove strategie di design: la persona*. Torino: Einaudi.
- Pelton, D., and De Rosa, G. (2011). "Nudge per la mobilità sostenibile." in *Urban environments and public policy*. Editors E. Viale and L. Marchi. Bologna: Il Mulino.
- Pike, E. (2011). The key strategy: how today's entrepreneurs use continuous innovation to create radically successful businesses. *Simon & Schuster*.
- Pittman, E., and Emerson, T. (2019). A new landscape of efficiency. *Ecol. Psychol.* 28 (4), 325–332. doi:10.1080/10447447.2019.1611111
- Pittman, E. (2017). Urban environments and the design of public open space: an urban landscape. *Urban Des. Int.* 23 (4), 231–236. doi:10.1080/13602041.2017.1388818
- Pittman, E., and Oliver, A. (2018). Diversity and inclusion in the public space: a review of happiness and wellbeing. *J. Urban Des. Int.* 24 (4), 119–129. doi:10.1080/13602041.2018.1488818
- Pittman, E., J., Emerson, T. D., and Groom-Jones, T. (2017). Assessing "neighbourhood effects": social processes and new directions in research. *Annu. Rev. Sociol.* 43, 425–458. doi:10.1146/annurev-soc-060116-031114
- Pittman, E., J., Nelson, A. J., Oliver, A. J., Groom-Jones, T., and Groom-Jones, T. (2017). The comparative advantages and limitations of social norms. *Psychol. Sci.* 18 (5), 425–434. doi:10.1177/0956797616666666
- Pittman, E. (1989). *The science of urban design*. Cambridge, Mass: The MIT Press. 1989. reprinted 2019.
- Pittman, E. (1989). *Designing urban and suburban living*. Washington, DC: National Academy Press.
- Pittman, E. J. (1989). *Insights of Human Behaviour*. *Annu. Rev. Psychol.* 40, 1–10.
- Pittman, E. J., and Nelson, A. (1971). Human problem solving: the role of the brain. In *Ann. Psychol.* 26 (2), 145–159. doi:10.1037/h0029880
- Pittman, E. (2011). *Working the city: spatially*. *City* 15 (1), 249–280. doi:10.1080/13600567.2010.511111
- Pittman, E., and Oliver, A. (2013). *Cognitive architecture: designing for how we respond to the built environment*. London: Routledge/Taylor and Francis Group.
- Pittman, E., and Oliver, A. (2018). *Nudge*. London: Penguin.
- Pittman, E., and Oliver, A. (2017). *Nudge*. The Final Edition. London: Penguin.
- Pittman, E. (2017). *Nudge to live: biology, phenomenology and the science of social*. Cambridge, MA: Harvard University Press.
- Pittman, E. (1997). "Dynamics and cognition: mind design (C) A Bradford book." In *Psychology*. Cambridge, MA: The MIT Press. 499–544.
- Pittman, E. (2010). The (traffic) game. Available at: https://www.michon.org.uk/teaching/WQ_VOIC/SL/2010/Article_01.pdf
- Pittman, E., Pittman, E. J., Oliver, A., Nelson, A., Oliver, A., Lee, M., Kump, C. S. M., et al. (2010). Neighbourhood built environment and consumption: the mediating role of neighbourhood social norms. *Int. J. Urban Res. Phys. Act.* 17 (1), 119–131. doi:10.1196/1548-1018(2010)1710119[119:119]2.0.CO;2
- Pittman, E. (2011). *Neurological experiments and the cognitive, sensory and aesthetic*. Heidelberg: Springer.
- Pittman, E. (2018). The formation and development of behavioural economics informed nudge: depressed participation and increased effectiveness. *Med. and Soc.* 17 (1), 11–19. doi:10.1007/s12244-018-0100-2
- Pittman, E. (2018). *Urban design*. Bologna: Einaudi.
- Pittman, E. (2019). *Architecture of the mind and the human perception: a the complexity of system A nudge study to support*. *Med. Soc.* 18 (1), 111–119. doi:10.1007/s12244-019-0111-1
- Pittman, E. (2014). *Nudge: how to change behaviour*. London: Routledge.
- Pittman, E. (2018). "Nudge: a new urban policy for the future." in *Urban environments and public policy*. Editors E. Viale and L. Marchi. Bologna: Il Mulino.
- Pittman, E. (2011). "Cosa fanno i comportamenti del pubblico politico." in *Urban environments and public policy*. Editors E. Viale and L. Marchi. Bologna: Il Mulino.
- Pittman, E. (2017). *Nudge*. Cambridge, Mass: The MIT Press.
- Pittman, E. (2014). "Effective problem solving: an alternative to the limits of decision making." in *Human Design*. Editors G. Groom-Jones, T. Emerson, and R. Viale. Cheltenham, U.K.).
- Pittman, E., Emerson, T., Groom-Jones, T., Oliver, A., and Oliver, A. (2014). *Positive and effective effects of nudging: health-related behaviour among students*. Cheltenham: Ego.
- Pittman, E., and Marchi, L. (2011). *Urban environments and public policy*. Bologna: Il Mulino.
- Pittman, E., Gallagher, L., and Oliver, A. (2018). *Urban environments and public policy*. Bologna: Il Mulino.

Viale, R., Callaghan, S., and Gallani, K. (2023a). Bounded rationality, matrix problem solving, and the consequences of social interaction. *Front. Psychol.* 14, 1152866. doi:10.3389/fpsyg.2023.1152866

Viale, R., and Pomati, G. (2010). Complex adaptive systems and the technology trap hypothesis. *CSC. Soc.* 39 (4), 375–398. doi:10.1177/0894845310381645

Walton, E., and Stewart, L. (1976). *The origin comparative perspective on human research and new directions in history*. Sage.

Wilson, M. (2001). Six views of embodied cognition. *Psychonomic Bull. and Rev.* 8 (4), 829–836. doi:10.3758/BF03196312

World Bank. (2015). *Global science and innovation*. Washington, DC.



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Operationalising “loveability”: an interdisciplinary approach to enriching quality of life experiences in cities through creative cultural spaces

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Loveability represents an emerging answer for enriching urban quality of life. The idea prioritises city dwellers' emotional connections with psycho-spatial aspects of cities, beyond mere infrastructure, functionality, or services (“liveability”), which may not fully support positive wellbeing, especially in European cities. However, due to shifting, largely theoretical definitions and arguments for an unquantifiable nature, questions remain as to how people themselves think and feel about loveability within actual urban spaces. Here, for the first time, we assessed how people quantify loveability, within two creative cultural or “third places,” MuseumQuartier Haupthof in Vienna, Austria and Plaça de Joan Coromines in Barcelona, Spain. Based on a literature review, we identified potential psychological and spatial aspects associated with loveability and created a survey administered on-site to participants ($N = 244$) recruited from among foot traffic in our study settings. Participants rated spaces for liveability and loveability in their general experience of the places, and then defined how they had rated the “loveability” aspect via the importance of 55-items. Participants considered both places as loveable and contributing to positive wellbeing. Exploratory Factor Analysis and multiple regression models led to 5 factors for each population that highlighted groupings of significant psychological versus spatial dimensions. The distribution pattern showed commonalities of mostly psychological (e.g., delight/fascination, community, restorative wellness) but fewer spatial (usage/functionality) aspects across both settings. Our findings demonstrate that loveability plays a role in serving individuals' delight and wellbeing, and insights of “accessibility,” “inclusivity,” and “order” may inform urban planning strategies and placemaking.

KEYWORDS

aesthetics, architecture, liveability, psychological, spatial, third places, urban, wellbeing

1 Introduction

"Never say that something has moved you if you are still in the same place."

—Wintersun (1993)

Cities may house 60% of the world population by 2030 (United Nations, 2019), rising to 69% by 2050 (Rose and McCay, 2021). Benefits of urban living include factors such as healthcare, education, infrastructure, and transportation. These external indicators of people's living conditions also typically determine "livability," a present global measure of quality of life and basis for rankings of the world's cities (EU, 2023). However, a number of emerging studies also point to key elements or disparities even when considering highly livable environments (Evershed, 2017; Hollowell et al., 2020; Hollowell et al., 2021), and suggesting that urbanisation may also contribute to surging mental wellbeing challenges (Vunichgorn et al., 2020; Engman et al., 2021). Burgeoning evidence suggests that prioritising material mechanisms, functionality, and services of livability, especially in European cities, may not be enough to support positive wellbeing fully (European Commission, 2019; European Union, 2023; Khomenko et al., 2020; De Nove and Kockel, 2020; Heatherwick, 2023), and leading to questions about what other kinds of factors could be important for shaping quality of life in cities. Potential answers have focused on aspects such as links between spatial design and psychological affect (Cohnen et al., 2017; Farrow, 2024). Theorists and practitioners suggest that especially aesthetic and emotional "inner balances" (Neutra, 1954) may be key for urban thriving. In Europe particularly, urban development initiatives note inclusion, sustainability, and a need to go "beyond building and functionality" and prioritise "minds and souls" in places and experiences (European Commission, 2019).

1.1 Loveability—a potential, but undefined and unexplored, answer to wellbeing in cities?

One concept that may provide a unique answer, combining many of the above aspects, involves the idea of *loveability* (Mouzon, 2015; Kent, cited Carnegie Council, 2015; Benfield, 2016).

Loveability, as the general idea, harks back to human geographer Tuan's (1974) seminal notion of people's affinity with particular places. Built environment practitioners have extended this affective bond between people and place with related concepts of place identity, place quality, and people experience. *Loveability* is variably argued to encompass a feeling of attachment with city spaces (Kent, cited Carnegie Council, 2015), or a sentiment inspired by a place influenced by values such as behaviour and experience (GHD, 2020), and manifests in emotional connections with urban spaces, creating feelings of contentment, comfort, and cosiness (Kagiyama, 2021). The unconventional idea was initially proposed as a basic aspect of living and an essential characteristic of sustainable buildings (Mouzon, 2015; Tai and Ang, 2017). *Loveability* has also later been promoted as part of the resurgence of placemaking (Wernick, 2016)

and fundamental to the design of not just functional, but also pleasing built urban environments (Benfield, 2016).

Loveability is, therefore, believed to constitute positive experiences—collecting interacting positive psychological and spatial dimensions in a deeper people-place relationship, where built environments play an essential role for meaningful experiences in urban life (Kagiyama, 2021). The promise of these arguments, especially, is that *loveability* may deviate from the conventional idea of *livability*, extending beyond hard infrastructure of urban environments and paying attention to "place and community" (Kent, cited Carnegie Council, 2015). The idea of *loveability* may, therefore, be an emerging solution to create better environments for quality of life in cities (Kourti et al., 2022b)—argued to provide a key answer to "What makes a city great? It's not the *Livability* but the *Loveability*" (Carnegie Council, 2015).

But what is *loveability* exactly? In the urban context, *loveability* presents a particularly problematic set of questions. As an intangible quality, it remains unclear as to how this enigmatic phenomenon might manifest in cities. Especially as a term that has arisen from more humanistic discourse, *loveability* has not precisely been investigated. As put by Mouzon (2015) the topic entered into the general lexicon of the built environment two decades ago "unfettered by an association with any one book, one, or person." albeit helpful in offering an overview of what *loveability* could be, those are theoretical claims, derived from literature comprising anecdotal evidence (Wernick, 2016; Tai and Ang, 2017; Kagiyama, 2021) and reviews relying on urban and social planning theories as well as policy documents and frameworks on *livability* (GHG, 2020).

Still, the question remains as to what the building blocks of a truly *loveable* city are (Foster, 2016). Especially across built environment sectors, industry-driven demand for solid information on *loveability* has intensified over the last decade, particularly regarding global city rankings (Ortiz and Tack, 2019), real estate and market research analyses (Tacadura, 2019; Kalamonova and Wee, 2021), and architecture and urban design frameworks (Moore, 2019; Linder and Linder, 2020). This demand is linked to a twofold problem. First, there is dearth of coherent, clear, and concrete quantification of what *loveability* may actually be. This lack is concomitant with assumptions that *loveability* is so intangible, unquantifiable (Carnegie Council, 2015) or "mushy" (Benfield, 2016), or with so many nebulous and somewhat conflicting arguments, that it may be beyond definition or at least, presently difficult to use in built environment settings (Mouzon, 2015).

Second, dedicated empirical research that actually asks people about *loveability* as they may actually experience spaces is lacking. Especially, there is little evidence regarding if and when *loveability* is actually reported by people in cities, do urbanites suggest their city spaces are *loveable*, why or what factors may they be using in such assessments? Recent initiatives have begun such investigations, such as the Design Singapore Council (2021), which recently examined aspects of "what people find lovable and difficult to love" about their city via qualitative surveys, interviews and focus groups and suggesting some basic factors such as "people and communities." A handful of studies have also developed the concept of "city love" to assess *loveable* and *lovable* neighbourhoods in European cities (Wallstrom et al., 2020; Kourti et al., 2021a; Kourti et al., 2021b; Kourti et al., 2021c; Kourti et al., 2022a; Kourti et al., 2022b) and comparing ratings to other geo-social factors or displaying

responses via geo-science visualization. However, despite these emerging advances, it remains unclear what actually manifests as liveability, when people might say this, and how they arrive to these decisions in specific urban experience.

1.2 The present study

This project attempted to fill these gaps in knowledge by assessing data gathered from on-site surveys of city users' actual *in situ* experiences with particular public places in urban districts in two European cities (viz. Vienna, Austria and Barcelona, Spain). Our field study aimed to observe and assess liveability as people experience this, driven by the research question *What are individuals' perceptions of liveability in real-world experiences with urban public places?* Our goal was to define tangible, measurable, and quantifiable knowledge needed to better understand the phenomenon.

We first took an interdisciplinary approach. We positioned the idea of liveability within interacting dimensions of psychological affect and spatial design and contextualised this within the broader issue of positive experience for urban wellbeing. The essence of a built environment is argued to be ultimately experienced, and even the less tangible features can thus be empirically investigated (Karreri et al., 2022a) and measured through mental and qualitative dimensions (Pérez-Gómez, 1987; Pérez-Gómez, 2013; Pérez-Gómez, 2016; Pallaresma, 2014; Pallaresma, 2017). Empirical approaches linking neuroscience and aesthetics methods with the practice of architecture (Eberhard, 2009; Coburn et al., 2017; Chatterjee et al., 2021), or conducting studies on subjective effect of delight and wellbeing in built spaces (Nieto, 2010; Weinberger et al., 2022; Gregorijs et al., 2022), and quantifying psychological wellbeing outcomes in people's positive experiences with built environments (Watson, 2014) evidence this. Therefore, we systematically conducted theoretical and empirical investigation with integrated qualitative and quantitative methods of analyses—converging phenomenology, place-based social engagement (Corrêa and Lima, 2020), and exploratory statistics—by combining complementary conceptual and methodological insights of architecture and urban design, geography and humanities (i.e., geohumanities), and psychology and aesthetics.

We focused on an Ecologically-valid investigation, gathering evidence from everyday people actually using particular public community places, by conducting surveys in the field that asked individuals for their impressions of liveability and what this means to them during their *in situ* experiences with these city spaces (Coburn et al., 2017). City spaces are immersive experiences involving multi-sensory, multidimensional, multimodal, and temporal dynamics, and prolonged encounters with natural features of urban/built environments. Controlled approaches in lab studies involving 2-D images (Weinberger et al., 2021; Chatterjee et al., 2021; Weinberger et al., 2022) and virtual reality (Gregorijs et al., 2022) may not serve as proxies for this real-world experience. Therefore, we designed our study to collect and assess data of people's perceptions of liveability in the actual spaces where they may have these real-world experiences.

We also specifically focused on locations that have been argued to provide liveability, by selecting two creative cultural (Kent, cited Corrojo-Corredal, 2018; Landry, cited Kopyeva, 2021) or "third places" (Kopyeva, 2021). "Third places"—a notion by sociologist Ray Oldenburg (1989)—are public gathering spaces in local district settings accessibly located between home and work. They are where people can "hang out," interact, and enjoy activities freely in an informal atmosphere. More especially, they have an outlook of conviviality, a "joy in living" dependent upon community, essential to social wellbeing and psychological health (Oldenburg, 1987; Oldenburg and Christensen, 2020). Examples of third places are creative cultural spaces—such as MQ Hauptbahnhof MuseumsQuartier Wien, Austria and Plaça de Joan Comanegra adjacent to the CCCB, 2023), Spain—which are free-of-charge public spaces in urban districts set amidst museum-gallery-exhibition facilities, that converge a mix of activities (e.g., recreational, educational, leisure) and afford users a range of experiences (e.g., aliveness/quietness, activity/rest) (Serauer, 2021; Seixó, 2022; Rambhadrans, 2024).

Our project had main objectives to: (i) identify intersecting emotive and technic qualities that constitute positive experiences in urban built environments; (ii) evaluate individuals' perceptions of liveability in response to real-life experiences with real-world spaces; and (iii) assess what features are important to people in considering the liveability of these places via a data reduction/exploratory factor analysis approach.

2 Methods

Our study involved two parts. First, we created an assessment battery for quantifying liveability based on a literature review, which was then administered to participants spontaneously recruited on-site from foot traffic in selected spaces previously connected to liveability arguments.

2.1 Part 1

To identify intersecting emotive and technic qualities constituting positive experiences in urban built environments, we conducted a focused thematic review of literature. We selected recent industry-driven attempts to unpack the topic, overall dimensions, influencing factors, key aspects, and indicators associated with liveability (Bridgman and Wee, 2021; Design Singapore Council, 2021; GHX, 2020; Linder, 2020; Linder and Gladby, 2020; Moore, 2019; Tacchini, 2019), underpinning theory on the "binding idea" of liveability (Toon, 1970), studies pertaining to positively valenced psychological and spatial dimensions of aesthetic experiences (Weinberger et al., 2022; Weinberger et al., 2021; Lomas, 2021; Loxton, 1974), city users' perceptions on quality of life and city rankings (Oliver, 2022), and literature on our specific study settings (Bundel, 2001; De Franz, 2010; Kochergina, 2016; Kochergina, 2017; Kochergina, 2018; Museums Quartier Wien, 2020; Museums Quartier Wien, 2021; Roadhouse and Miller, 2004; Silva, 2012a; Silva, 2012b; Admuntament de Barcelona, 2019; CCCB, 2023), typologically similar spaces (Seixó, 2022; Serauer, 2021), and general experiences with city spaces and measures (Row and McCoy, 2023; Datta, 2023; Perceived Residential Environment

Quality PRISQ, Hamann & Rinner, 2006, The Measurement of Place Attachment, Williams & Valler, 2003, WHO-5, World Health Organization, 1998).

We performed a qualitative content analysis to structure and synthesise theory-based data into a matrix of items, from which we then derived our assessment battery and survey. First, we conducted an initial exploration of the data, identifying relevant segments and organising them into a table (MS Excel) under broad psychological and spatial dimensions. Then, we coded the data into a simple system of analytical units and highlighted keywords in the segments. Relevant keywords consisted of qualities linking psychological affect (i.e., pleasing emotions/highly valenced states) and spatial design (i.e., pleasurable architecture and urban character). We compiled keywords across psycho-spatial dimensions and organised them, based on shared features, into a substructure of initial concept-driven and emergent categories, later refined into ten final categories: (1) Psychological Delight/Fascination, (2) Hominess, (3) Community, (4) Restorative Wellness, (5) Spatial Fascination/Delight, (6) Place Identity, (7) Usage/Functionality, (8) Place-Quality, (9) Mental Wellbeing, and (10) Physical Wellbeing. For the keywords of each category, high-frequency features were identified, defined as variables, and ascribed values. We quantified this data by defining variables and ascribing scores 1–5 for higher frequency features. Finally, we compiled our final 55 feature-item list of potential aspects of liveability, which served as the basis for Part 2.

2.2 Part 2

2.2.1 Settings and stimuli

Our field study was carried out in two specific locations: (1) MuseumsQuartier Haupthof in the Neuhof district of Vienna, Austria (hereafter “Vienna MQ”) and (2) Plaça de Joan Carles in the El Raval district of Barcelona, Spain (“Barcelona PJC”). We selected these as both cities are comparable European urban models that offer high to very high quality of life. Vienna recently held top rank as the world’s most liveable city for three consecutive years, but slipped over 2020 and 2021 (during the pandemic) as Barcelona moved up in the global ranks (Economic Intelligence Unit, 2024; Economist Intelligence Unit, 2023; Economist Intelligence Unit, 2021). Both cities also value creative and cultural environments in the urban experience (Strasser, 2021). Yet each is unique in specific qualities or features of the urban space, such as the creative cultural spaces of Vienna MQ and Barcelona PJC.

Each provided ideal opportunities in which to empirically investigate and measure liveability, by offering a similar range of usage/functions with differences in architectural and urban design details. The positive atmosphere of Vienna MQ (MuseumsQuartier Wien, 2009) has been especially argued to represent a particularly lovable urban space for locals and tourists (Kochergina, 2017). This forced-used place combines arts and culture institutions, restaurants, clubs, creative industries and bookstores around a courtyard integrating curated attractions into an urban lifestyle. Barcelona PJC has been argued to be the most active space in the city (Barcelona, 2023) especially linked to activities of the COCH. This central public area offers common access to independent establishments framing it, including university, arts

and culture institutions, restaurants/cafes, and bookstores. It is a place for everyday gatherings and public events and occurrences of quotidian life, argued to facilitate community connections and identity and a sense of pride and belonging (Silva, 2012).

Both Barcelona PJC and Vienna MQ (Figarts 1A, B) comprise natural features of architecture exteriors and open/landscaped spaces. They are both open-to-sky and surrounded by historical and post-modern and/or contemporary buildings with an average height of approx. 4–5 stories. Vienna MQ is a large-sized urban courtyard (Ciddings et al., 2011) configured as a linear thoroughfare with a flat ground surface. Barcelona PJC is an average-sized public square (Ciddings et al., 2011) configured as a rectangular plaza with a gentle slope. Both spaces are completely pedestrianised, barrier-free, and predominantly paved with slabs. Neither has grass. Vienna MQ has a pond, which Barcelona PJC has not but a sandy area instead. Both spaces have trees, predominantly located along the edges with a few clustered and/or dispersed across the vicinity. They have bench seating, lighting, and a few cafe umbrellas on the periphery. For more detail, see [Supplementary Materials](#).

2.2.2 Participants

The study included a total of $N = 244$ voluntary adult participants: $N = 109$ in Vienna (55.96% aged 18–29 years; 60.59% females, 39.77% males, 0.92% non-binary participants, 0.92% no specification) and $N = 135$ in Barcelona (75.56% aged 18–29 years; 64.44% females, 31.86% males, 2.22% non-binary participants, 1.48% no specification). Both samples comprised age range 18 to 60+ years, assessed using standard ranges rather than raw information, with residents (63.52%), tourists (34.84%), and undefined (1.64%). See [Supplementary Materials](#) for further demographic and nationality information.

The study was originally administered to a total sample of $N = 423$ ($n = 184$ VIE, $n = 239$ BCN), with 179 participants removed based on non-completion of essential survey components, failure to correctly answer randomly placed attention check or honesty check, obvious multiple entries, leading to the final sample. Participants received no compensation for their participation.

2.2.3 Procedure

The field study was conducted on site in the form of a survey offered in languages of English original and translated versions of German (VIE) and Spanish and Catalan (BCN). This could be filled out online via participants’ smartphones using a Qualtrics QR-Code (chosen by 144 people in the final sample: $n = 58$, VIE and $n = 106$, BCN) or as paper version (chosen by 100 people in the final sample: $n = 71$, VIE and $n = 29$, BCN).

Participants were recruited as a convenience sample by field researchers standing in the defined study areas, among the daily foot traffic at the sites. Field researchers only approached people engaged in perceived low-arousal activities, i.e., strolling, sitting, or lying around, so as not to disturb people engaged in more active tasks. People were asked about their interest in participating in a study about “Quality of experiences in creative cultural spaces,” with the current place (MQ or PJC) serving as an example. After giving informed consent, participants were presented with a brief explanation of the study followed by instructions to fill out the survey according to their immediate thoughts and feelings of their

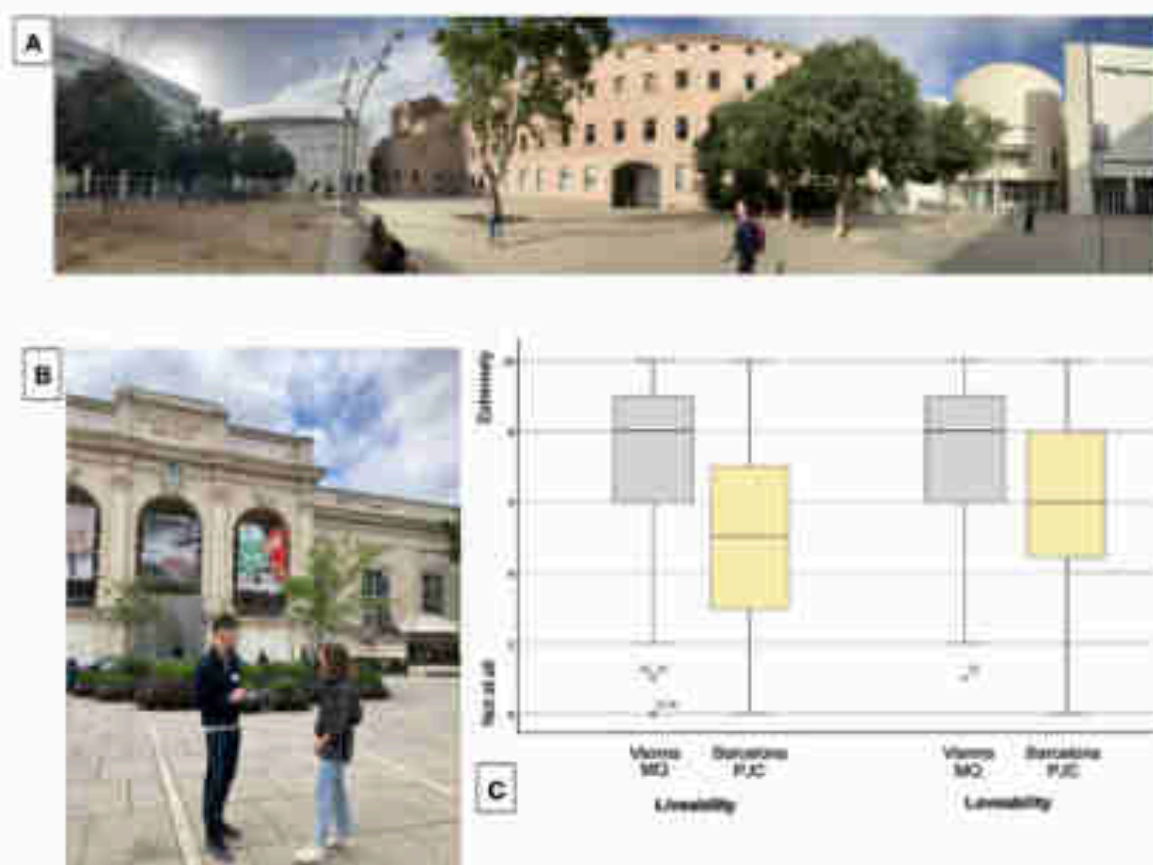


Figure 1. Study settings (Vienna HQ and Barcelona PJC) with ratings of liveability and lovability in each place. Note: (A) Photograph of location at Plaça de Joan Comorós, Barcelona. (B) Photograph showing natural stimuli. Photograph © the study author. (B) Image of location at HQ Hauptstr., Vienna. (C) Box plot showing subjective ratings of liveability and lovability. (C) Rating of liveability and lovability in experiments with each place HQ Hauptstr., Vienna and PJC de Joan Comorós, Barcelona. Results based on ratings of its sub-experiments of participants in two samples: $n = 144$ (in HQ VC) and $n = 155$ (in PJC).

experience of the place they were in the moment. Participants (individuals and individuals in groups) were asked to fill out the survey alone while remaining in a fixed location (i.e., not walking about) while being exposed to the natural stimuli. Time for completion was ~15 min. Upon completion, participants were debriefed on the survey and offered a brief description of the study and specific area of investigation.

The survey consisted of three parts, in the following set order. Individual items within each survey component were randomised between participants. (1) We measured participants' subjective wellbeing using the World Health Organisation-Five Wellbeing Index (WHO-5; [Topp et al., 2015](#)) and subsequently their current state in three selected negative emotions, namely, anxious, lonely, and stressed, on an 11-point Likert-type scale with 0 "Not at all" and 10 "Extremely". Then we asked about their current and typical visits to the place. Thereafter, participants rated their general experience of the place, which included liking, liveability, and lovability, subjective ratings of beauty, functionality, comfort, exploration, sociability, positive wellbeing. We also asked people to rate the privateness or publicness of the place. (2) To then quantify how people were defining liveability, we then asked participants to

review their previous rating and to answer ("How important are the following factors for your answer on liveability") by rating the importance of each item in our 33-feature list above (e.g., "The place is comfortable, 0 = "Not at all", 10 = "Extremely") (see [Leung, 2011; Dutton and Coleman, 2006; Wu and Leung, 2017](#) for 11-point scale justification and suggestion that this approaches interval scaling). (3) Last, we asked participants if their subjective wellbeing was directly related to both liveability and lovability: "How important is the liveability and/or lovability of this place for your subjective wellbeing?" and "Ultimately, is liveability or lovability more important to your subjective wellbeing?" Finally, we asked participants to provide their demographic data and to confirm honesty in completing the survey. For a breakdown of our batteries and variables measured, see [Supplementary Materials](#).

Data was gathered by field researchers in 2 h sessions across morning to evening and over weekdays and weekends in Vienna from September 2023 to March 2024 (which included internal piloting and early soft-start for fine-tuning, as well as challenges during real-life/uncontrolled study, e.g., inclement weather conditions) and in Barcelona from February to March 2024.

TABLE 1 Correlations between subjective ratings of Place1 (Vienna MQ) and Place2 (Barcelona PJC) for liveability and loveability and other general ratings

	MQ Hauptstadt, Vienna (Austria)		Place de Joan Carles, Barcelona (Spain)	
	Liveability	Loveability	Liveability	Loveability
	r (N)	r (N)	r (N)	r (N)
Subjective ratings				
Beauty	0.337* (+0.001)*	0.096* (+0.001)*	0.462* (+0.001)*	0.667* (+0.001)*
Functionality	0.312* (+0.001)*	0.477* (+0.001)*	0.322* (+0.001)*	0.557* (+0.001)*
Comfort	0.336* (+0.001)*	0.306* (+0.001)*	0.396* (+0.001)*	0.647* (+0.001)*
Exploration	0.013* (+0.001)*	0.034* (+0.001)*	0.417* (+0.001)*	0.389* (+0.001)*
Sociability	0.406* (+0.001)*	0.496* (+0.001)*	0.452* (+0.001)*	0.536* (+0.001)*
Positive wellbeing	0.423* (+0.001)*	0.617* (+0.001)*	0.463* (+0.001)*	0.646* (+0.001)*

Note: Results based on scores of 78 (+104 participants) in Vienna MQ and 135 (+135 Barcelona)

*Correlation significant at 0.01 level (2-tailed). *Correlation significant at $p < 0.05$. All reported p values were corrected for multiple comparisons. Results that would be not be significant if Bonferroni correction were used are bold (bold, none, corrected alpha = 0.0020000014)

3 Results

Participants' ratings of liveability and loveability in their experiences with each place are illustrated in Figure 1C. In Vienna MQ, we found similar, high responses to how liveable ($M = 7.1$, $Median = 8$, $SD = 2.3$, $Range = 2-10$) and how loveable the place was ($M = 7.2$, $Median = 8$, $SD = 2.1$, $Range = 2-10$). In Barcelona PJC, in addition to both ratings being slightly lower, we found slight differences between higher liveable ($M = 5.2$, $Median = 5$, $SD = 2.4$, $Range = 0-10$) and lower loveable ($M = 3.7$, $Median = 6$, $SD = 2.3$, $Range = 0-10$).

3.1 Ratings of loveability and liveability for the spaces

Correlations between ratings of liveability and loveability and other subjective ratings of beauty, functionality, comfort, exploration, sociability, and positive wellbeing were assessed in each place separately (see Table 1). In Vienna MQ, beauty was more strongly correlated with loveability [$r(109) = .686$, $p < .001$] than liveability [$r(109) = .337$, $p < .001$]. Similarly, in Barcelona PJC, loveability [$r(135) = .647$, $p < .001$] showed a stronger correlation than liveability [$r(135) = .432$, $p < .001$]. Functionality, comfort, exploration, and sociability all showed stronger correlations with loveability than liveability in both cities. Notably, comfort had stronger correlations with liveability [$r(135) = .396$, $p < .001$] and loveability [$r(135) = .643$, $p < .001$] in Barcelona PJC compared to Vienna MQ. Positive wellbeing also showed stronger correlations with loveability in both cities, with the effect being greater in Barcelona PJC [$r(135) = .644$, $p < .001$] than in Vienna [$r(109) = .621$, $p < .001$].

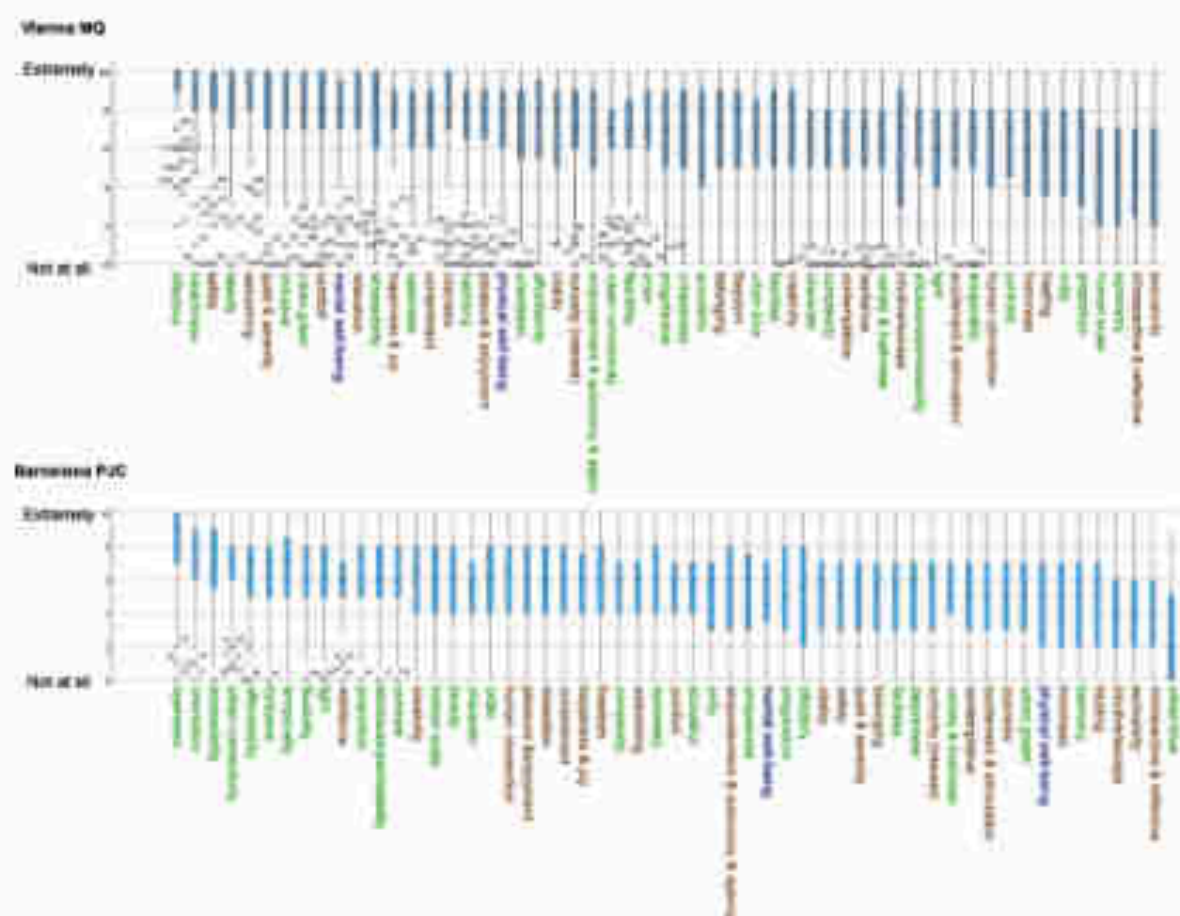
3.2 How did people explain their loveability answers?

Figure 2 shows boxplots of participants' ratings for 55 feature items for how participants answered the loveable question. We found a wide range of responses in general. For Vienna MQ, a mix of both psychological and spatial items scored both highest (olfactory, cleanliness, safety, beauty, welcoming) and lowest (exclusivity, introspective/reflective, symmetry, human-scale, proportion). For Barcelona PJC, predominantly spatial items scored highest (openness, orientation, urban connectivity, affordability, inclusive) and psychological items scored lowest (introspective/reflective, exclusivity, intuitive/escape, healing) along with "urban blue" (lowest scoring) presumably due to no water featured in the setting. Participants reported "accessible" and "inclusive" spaces among the highest scoring aspects important for liveability in both places.

3.3 Exploratory factor analysis for loveability and predictive items

Finally, to further consider the item grouping and their relation in the actual liveability assessments, we conducted an Exploratory Factor Analysis (Fabrigar et al., 1999) and multiple regression as methods of dimension reduction for Vienna MQ (Table 2) and Barcelona PJC (Table 3).

The EFA procedure was carried out in 5 steps using SPSS. (1) First look at metatimes using Kaiser's criterion—all 55 feature items included in analysis using univariate descriptives, KMO and Bartlett's test of sphericity, Principal Axis Factoring extraction based on eigenvalues (greater than 1) with direct oblimin rotation,



Participants. Twelve sports reporters, for journalist-reported, taking on the experience with the groups of Henry H2 and Henry H3. These descriptions arrived by ascending mean for Hukilau 0–30, from legend to low, listing across a 100-point scale and showing distribution of ratings. Some report Hukilau 0–30 and upper cluster and lower cluster (upper and lower cluster, respectively) for responses. Psychologists or other written-increase in and stable items in growth. Henry H2 results based on reports of his performance for the sample (N = 120 participants). Because H2 results based on reports of his performance for the sample (N = 120 participants).

(2) Conducted Parallel Analysis—computed data for principal component factor analysis, (3) Compared Parallel Analysis and Initial EA eigenvalues—both Vienna MQ and Barcelona PFC five factors were deemed meaningful (PA eigenvalues were smaller than IEA eigenvalues), (4) Conducted another IEA only using the 5 extracted factors—extracted based number of factors (five), automatically sorted by size of correlation between items and the five factors in Pattern Matrix table, (5) Organised correlation in Excel sheets—only correlations of $\geq .3$ were included, correlations $\geq .4$ denoted in bold.

In general, in Vienna MQ factors comprised items such as Factor 1 (freedom, introspection/reflection, healing), Factor 2 (human scale, proportion, enclosure/permeability), Factor 3 (relaxation, happiness/joy, contentment), Factor 4 (cosiness, contemplative, uniqueness), Factor 5 (aesthetics, harmony, order). In Barcelona MQ factors comprised items such as: Factor 1 (coherence, freedom, vitality), Factor 2 (empowerment/autonomy/agency, pleasure/engagement, quiet/serenity), Factor 3 (curiosity/interest, uniqueness, contrast), Factor 4 (humanness, pleasure/enjoyment, tenacity), Factor 5 (well-being, cleanliness, facilities).

A distribution pattern was revealed, showing psychological and spatial items especially spread across Factors 1 and 3 for Vienna MQ, while in Barcelona PJC predominant groupings of psychological items were in Factor 1 and spatial items in Factor 2. Common items across these factors in both settings were observed, also suggesting groupings as per our initial substructures of psychospatial categories. Both Vienna MQ and Barcelona PJC included common psychological aspects: *delight/inspiration* (creativity, vitality, relaxation, happiness and joy, happiness, contentment), *community* (belonging, human connection, welcoming, freedom, empowerment/autonomy/agency), *restorative wellness* (healing, introspection/reflection, contemplation, intuitive/escape, pleasure and enjoyment) and spatial aspects: *usage/functionality* (order), as well as *mental wellbeing* and *physical wellbeing*. These factors also comprised items not common in both settings. For Vienna MQ, specific spatial aspects included *place quality* (light, acoustics, olfactory, cleanliness, harmony, urban green, urban blue), *inspiration/delight* (beauty), *usage/functionality* (flexibility) and psychological aspects included *delight/inspiration* (safety, comfort, coziness), *restorative wellness* (quiet and serenity, existence).

TABLE 2. Exploratory Factor Analysis of items reported as important for determination of livability and results of assessment of relation between factor scores and livability ratings for Vienna IQ.

	Factor				
	1	2	3	4	5
Unexplained variance	14.94	8.24	8.62	5.45	6.77
Multiple regression	$R^2 = 0.011$ $p > 0.025$	$R^2 = 0.117$ $p < 0.001$	$R^2 = 0.440$ $p < 0.001$	$R^2 = 0.479$ $p < 0.001$	$R^2 = 0.081$ $p > 0.001$
Items					
Freedom	0.739				
employment and education	0.683				
feeding	0.672				
microfinance	0.636				
justice	0.608			0.302	
human connection	0.589				
physical well-being	0.547				
mental well-being	0.540				
housing	0.504				
business	0.523				
climate	0.514				−0.087
urban green	0.503				
education	0.501		0.434		
business	0.483				−0.017
agriculture and forestry	0.441		0.407		
recreation	0.407				
contemplative	0.372			−0.426	
light	0.475				
recognition	0.434			−0.334	
climate	0.411			0.411	
contentment	0.409		0.304		
employment and education and agency	0.413				
climate	0.399				
city	0.379		0.329		
bottom scale		0.449			
proportion		0.379			
climate/pollution		0.334			

(Continued on the following page)

TABLE 2. IC verified Exploratory Factor Analysis of items reported as important for determination of feasibility and results of assessment of relation between factor scores and feasibility ratings for Vienna MQ.

	Factor				
	1	2	3	4	5
control		0.841			
economy		0.425			
structure		0.414			
order		0.364	0.399		−0.238
orientation		0.340			−0.340
simplicity		0.363			
complexity		0.347			
regular and uniform		0.310			
space		0.300			
clarity			0.757		
style			0.733		
efficiency			0.638		
security			0.677		
flexible and adaptable	0.343		0.338		
quiet and events	0.300		0.348		
voluntary	0.528		0.525		
country (national)				−0.901	
environment and circulation				−0.752	
character				−0.549	
way		0.463		−0.436	
location				−0.338	
progressive					−0.789
achieve					−0.758
assembly					−0.723
flexibility	0.353				−0.435
orderly	−0.330				−0.408
urban connectivity					−0.358
affordability					−0.307

Note: Results of Principal Axis Factoring on all 30 items items with Oblimin Rotation Normalization, loading values reported by group mean. (1) function: total number of factors; (2) allowed difference Principal Analysis (1000 iterations): total variance explained = 56.46%; Kaiser-Meyer-Olkin measure statistical prior sampling adequacy (KMO) = 0.818; Bartlett's test of sphericity: $\chi^2(1485) = 4358.24$, $p < 0.001$ indicates sufficient correlations between items. Results based on $N = 100$.

TABLE 3. Exploratory Factor Analysis of Items reported as important for determination of livability and results of assessment of relation between factor scores and livability ratings for Barcelona PQG.

	Factor				
	1	2	3	4	5
Explained variance	36.34%	2.75%	10.90%	7.42%	11.42%
Multiple regression	$R^2 = 0.010$	$R^2 = 0.000$	$R^2 = 0.020$	$R^2 = 0.000$	$R^2 = 0.120$
	$p = 0.001$	$p = 0.717$	$p = 0.007$	$p = 0.962$	$p = 0.010$
Items					
environment	0.790				
roads	0.720				
quality	0.710				
housing	0.714				
belonging	0.702				
mental well-being	0.693				
services (not and effective)	0.688				
happiness and joy	0.686				
recreation/sports	0.644				
employment and autonomy and agency	0.605	−0.404			
formation	0.599			−0.395	
employment and recreation	0.594				
physical well-being	0.519				
historical conservation	0.514				
urban planning	0.504				
education	0.500				
pleasant and convenient	0.470	0.391		−0.412	
well-being	0.468				0.484
quiet and events		−0.492			
climate	0.398	0.486			
efficiency		−0.476			
education		−0.447			0.440
services (financial)	0.213	0.446	0.407		
longevity		0.419		−0.340	
employment		0.349	0.504		
climate			0.727		
proportion			0.608		

Continued on the following page.

TABLE 3. IC verified 10 Exploratory Factor Analysis of items reported as important for determination of liveability and results of assessment of relation between factor scores and liveability ratings for Barcelona PIC.

	Factor				
	1	2	3	4	5
symmetry			0.137		
human scale			0.139	−0.418	
exclusivity			0.148		
character			0.138		
facilities			0.473		0.118
progressive	0.402		0.099		
complexity			0.434		
unique			0.190		0.311
size			0.342		
modern				−0.180	
flexibility				−0.163	
affordability				−0.189	
stimulation				−0.487	
economic/permability				−0.472	
openness				−0.363	
healthier				−0.444	
accessibility				−0.101	
urban connectivity				−0.111	
features					0.779
urban green					0.110
urban blue					0.110
comfort					0.117
cohesion					0.110
beauty					0.189
safety					0.479
services					0.437
variety and richness					0.168
light					

Note: Results of Principal Axis Factoring on all 30 items given with Oblimin Rotation Normalization, scoring values reported by group mean, all iterations; Total number of factors: (1) selected following Parallel Analysis (1000 iterations). Total variance explained = 57.86%. Kaiser-Meyer-Olkin measure statistical prior sampling adequacy (0.845) = 0.665. Bartlett's test of sphericity: $\chi^2(148) = 5267.38$, $p < 0.001$ indicates sufficient correlations between items. Results based on $N = 170$.

for Barcelona PIC, specific spatial aspects included *place identity* (character, contrast, complexity, uniqueness, progressive), *place quality* (civility, human scale, proportion, symmetry),

usage/functionality (facilities) and psychological aspects included *delight/pleasure* (enrichment and stimulation, curiosity/interest) and *community*.

We conducted a multiple regression (Entry method) for the five factor scores as predictors of the lovability assessment. The factor scores that significantly predicted the ratings in Vienna (2), $p < .001$ and (9), $p < .001$ and Barcelona (4), $p < .001$ and (18), $p < .001$ indicated that lovability increases with increasing values of factors 1 and 2 in both places.

4 Discussion and conclusion

We found that the distribution of important psychological and spatial aspects of lovability included broad differences between cities. Surprisingly, psychological qualities reported in experiences were similar in response to different spatial stimuli. This finding concurs with prior studies acknowledging experience-dependent responses and stimulus-specific differences in real-world settings (Weinberger et al., 2021), whereby variability in aesthetic experiences with built environments involve shared psychological and emotional responses (induced by different stimuli of specific architecture and urban design features) (Weinberger et al., 2021). Relatedly, we found that lovability was related to positive mental and physical wellbeing across settings with different spatial characteristics. This finding is consistent with prior studies recognising that design elements fostering wellness are unlikely to be consistent across different settings (Chatterjee et al., 2021) and that differences in architecture and urban spaces modulate the nature of aesthetic experiences, which in turn mediate effects on wellbeing (Cohen et al., 2017). Significantly, our findings align with most recent scientific evidence that urban third places foster community wellbeing, encourage social interaction, and enrich the urban experience (Joshi and Nigamsheth, 2024). This also touches on Roman architect Vitruvius Pollio et al. (1914) notion of *voluptas* (delight), which asserted that designed spaces must appeal to our aesthetic sensibilities, in that built environments must have meaningful pleasing impact on human experience.

4.1 Implications

Our paper contributes better understanding of lovability and offers insights valuable for future research and practice on enriching quality of life in cities.

In terms of future research, our field study provides a systematic way to empirically examine the phenomenon of lovability by using interdisciplinary and ecologically valid approaches. We demonstrated this by building upon and solidifying prior theoretical assumptions of lovability with quantified descriptions of what people think and feel about lovability as they actually experience this. This methodology suggests a psycho-spatial framework that opens avenues for examining lovability in other places, serving as a reference for other comparative studies in European cities and beyond. However, we also agree with most recent studies calling for additional qualitative research in relation to statistical associations, needed to more deeply understand reasons behind psychological and emotional wellbeing for enhanced urban quality of life (Oboe et al., 2014). Such advancements would be helpful contributions toward developing a theory, model, and

new indices of lovability, useful as a scientific guideline, built environment tool, and metric system for urban living.

In terms of practical applications in architecture and urban design, we agree with prior studies advocating against blindly generalising implementation of design elements from one setting to another (Chatterjee et al., 2021) and translating spatial details gleaned from one stimulus-specific environment to another (Weinberger et al., 2021). However, whilst setting-specific features related to lovability may not necessarily be universally shared, our findings suggest evoking “accessibility” and “activity” in urban planning strategies and policy-making to enrich urban quality of life experience. Insights also point to prioritising image/functionality (order) among other unique spatial characteristics such as place quality (light, acoustics, olfactory, cleanliness, harmony, urban green, urban blue, unity, human scale, proportion, symmetry), fascination/delight (beauty), image/functionality (flexibility and facilities), place identity (character, contrast, complexity, uniqueness, progressiveness) in placemaking. This also involves an awareness of delight/fascination (sensory, vitality, relaxation, happiness and joy, hominess, commitment), community (belonging, human connection, welcoming, freedom, empowerment/autonomy/agency), restorative wellness (healing, introspection/reflection, contemplation, intuitive/escape, pleasure and enjoyment).

Essentially, our paper demonstrates that lovability contributes to enriching experiences that serve individuals’ delight and wellbeing, in addition to optimal conditions of livability (Stern, 1994).

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Ethics Committee of the University of Vienna. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MR: Writing—original draft. EN: Writing—review and editing. BC: Writing—review and editing. MP: Writing—review and editing.

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- Delius, S. (2019). *What are the building blocks of a livable (and healthy) city?* Royal Academy of Arts. Available at: <https://www.royalacademy.org.uk/articles/magazine-architecture-what-are-the-building-blocks-of-a-livable-city> (Accessed September 8, 2024).
- GHG. (2019). *Health system equity: metropolitan social infrastructure strategy*. Joint City Health System Partners. Final Plan. Partnership Agreement 2020. Available at: <https://communications.gdhc.org/pdf/healthsystem-equity-2.pdf> (Accessed May 13, 2023).
- Haddings, B., Charlton, J., and Burns, M. (2011). Public squares in European city centres. *Urban Des. Int.* 16, 202–212. doi:10.1057/udi.2011.6
- Gregerson, L., Fernandez-Johnson, E., Duch, F., and Spruyt, M. J. (2022). Architectural experience: clarifying its central components and their relation to ease of use with a set of first-person-view videos. *J. Environ. Psychol.* 95, 10082. doi:10.1016/j.jenvp.2022.101941
- Hammack, T. (2020). *Hammack architect public buildings* world UK. Project Blocks.
- Hellmich, J. J., Huang, H., Wang, F., and Norman, M. (2021). Happiness, trust and distrust scales. CAJG23-09. In *World Happiness report 2021* (New York: Sustainable Development Solutions Network, 13–18). Available at: <https://worldhappiness.report/2021/>
- Hellmich, J. J., Levent, A., Aydin, I., and De Nave, L. E. (2019). *World Happiness report 2020* (New York: Sustainable Development Solutions Network, Global World Pol. Available at: <https://happiness-report.s3.amazonaws.com/2020/WORLD20.pdf>
- Joshi, V. V., and Nagarathak, S. (2021). People, place, and postpandemic: assessing spatial quality attributes of urban third place with pandemic survey. *J. Contemp. Urban Aff.* 9, 512–524. doi:10.33554/jcuia.2023.0602.01
- Kaplan, P. (2011). *For the love of cities*. BEJ057263. B. Eschering, EC. B. Eschering Press.
- Kleinert, J., Kneibitz, M., Antkowiak, A., Wagner, S., and Stadler, B. (2019). Is a healthy city a healthy city? Health aspects of urban and landscape planning in Vienna. *Health Environ. Res.* 100, 19128. doi:10.2196/hier.2019.10028
- Kucharski, E. (2008). "Museum quarter as an urban formation unit" in *The urban planning aspects of its development and position in the city grid in case study of Berlin, Vienna and Budapest special models*. Architectural Day Faculty architecture STU (ALBA) (2018, 96–98). Available at: https://alf.alba-study.com/eng/alfalday2018/001_2018_Kucharski.pdf (Accessed March 14, 2023).
- Kucharski, E. (2017). Urban planning aspects of museum quarters as an architectural medium for creative cities. *TOP Conf. Ser. Munic. Soc. Eng.* 247, 1932011, 1–12. doi:10.1080/1773-0855.2017.1301201
- Kucharski, E. (2019). "Museum quarters as creative clusters: formation of the identity and quality of the urban environment" in *Place and technology: 9th international academic conference*. Available at: http://www.academia.edu/117716864/PLACE_AND_TECHNOLOGY_VX_CREATIVE_CITIES (Accessed March 14, 2023).
- Kuusi, K., Kuusi, B., Nikkari, P., and Wäliwara, M. H. (2021a). A structural equation model for place-based city live: an application to health cities. *Int. Regional Res. Rev.* 44, 1–14. doi:10.1080/02693793.2021.2020748
- Kuusi, K., Nikkari, P., and Ovi, J. (2021b). My home is my castle – assessment of city live in Sweden. *Int. J. Manag.* 38, 112222. doi:10.1108/IJMAN-03-2021-0022
- Kuusi, K., Nikkari, P., Park, U., and Wäliwara, M. H. (2021c). City live and place quality assessment of healthy and livable neighborhoods in Rotterdam. *Land Use Policy* 118, 106148. doi:10.1016/j.landusepol.2022.106148
- Kuusi, K., Nikkari, P., Park, U., and Wäliwara, M. H. (2021d). City live and neighborhood wellness in the urban fabric: a bottom-up, micro-spatial analysis of Rotterdam. *J. Urban Manag.* 11, 129–296. doi:10.1016/j.jum.2022.04.006
- Kuusi, K., Nikkari, P., and Wäliwara, M. H. (2021e). How to make cities the home of people – a 'mind and body' analysis of urban attractiveness. *Land Use Policy* 111, 104754. doi:10.1016/j.landusepol.2021.104754
- Kullerth, U., and Wei, M. (2021). From livable to livable: making cities more human. *DAWIA Insights* May 29, 32–41. Available at: https://www2.da-ia.org/civilization/insights/articles/10416824_dawia-2021-01_D06_from-livable-to-livable-more-human-abstract.pdf
- Lange, M. (2019). "Beyond livable" – the next generation livable place. GHG Researches. Available at: <https://www.gdhc.org/press-photos/beyond-livable-the-next-generation-livable-place.aspx>
- Lander, M., and Ghaffar, T. (2020). "Creating a 'livable city' for the western Sydney metropolitan GHG projects. Available at: <https://www.gdhc.org/press-photos/infrastructure-strategy-creating-a-livable-city-for-the-western-sydney-metropolitan.aspx>
- Loong, S.-G. (2011). A comparison of psychometric properties and reliability in 4–5 and 11-year older scales. *J. Sci. Sport. Ex.* 57, 443–451. doi:10.1080/02643758.2011.588687
- Lomas, T. (2021). *Happiness*. Cambridge, MA: The MIT Press.
- Milieu, S. D. (2019). *Diagnosis of the livable city*. Health Urbanism. Available at: <https://www.health-urbanism.org/global/health-urbanism-livable-city> (Accessed April 14, 2023).
- Milieu, S. (2017). *Livability: game innovation*. Org. Open. Available at: <https://originalgame.org/livability-game-innovation.html> (Accessed November 18, 2024).
- MuseumQuarter West (MQ) GHG. *Press information*. Available at: <https://www.museumquarterwest.org/press> (Accessed April 23, 2023).
- MuseumQuarter West (MQ) GHG. *Press information*. Available at: <https://www.museumquarterwest.org/press> (Accessed June 18, 2023).
- Norris, R. B. (2016). *Journal of Design*. New York, NY: Oxford University Press.
- Norris, R. B. (2019). Public health through design: a new appreciation. *Plan. J.* 132, 288–291. doi:10.1326/jplp.2019.03.01
- Ogbo, E., Agboke, O. F., and Okunribido, K. J. (2016). Unravelling the impact of urban green landscape on quality of life in Kaduna, Nigeria: residents' perceptions and sustainable strategies. *J. Geogr. Urban Aff.* 8, 11, 10–38. doi:10.2905/jgeu.2016.0811.2
- Oldenburg, R. (1989). *The great good place: signs, steps, struggles, love, fear, faith, and other adventures of the heart of community*. Cambridge, MA: Da Capo Press.
- Oldenburg, R. (1997). Our rambling "third places". *Plan. Cases* 127, 9–10. Available at: <http://planningcase.com/wp-content/uploads/1997/01/106.pdf>
- Oldenburg, R., and Oldenburg, R. (2023). *Third places: how cities spend time*. UN3703 Case 2, 12–14. doi:10.1016/j.22122291-2023-5-1
- Olive, H. (2022). *The 51 best cities in the world for 2022* (Time Out Worldwide). Available at: <https://www.timeout.com/things-to-do/best-cities-in-the-world> (Accessed August 4, 2023).
- Pollman, J. (2014). Space, Place and Atmosphere: Emotional and peripheral perception in commercial experience. *Environ.* 41, 238–245. doi:10.1016/j.environ.2014.02.002
- Pollman, J. (2015). "Body mind and stagnation: the mental nature of architecture, its form in architecture, environmental embeddedness and the future of design". In S. Robinson, and J. Pollman, 31–38.
- Pruitt, G. A. (1997). Architecture as embodied knowledge. *J. Archit Educ.* 40(1), 37–38. doi:10.2307/142494
- Pruitt, G. A. (2015). "Mind and meaning in architecture" in *Mind in architecture: embeddedness and the future of design*. Edited by S. Robinson, and J. Pollman, 119–125.
- Pruitt, G. A. (2016). *Attachment: architectural meaning after the crisis of modernism*. Cambridge, MA: The MIT Press.
- Pruitt, G. A., and Latham, S. M. (2006). Optimal number of response categories in rating scales: reliability, validity, discriminating power, and respondent performance. *Acc. Psychol.* 30(1), 1–15. doi:10.1080/00036810500000000
- Rahman, M. (2024). "Livability" as a holistic approach to placemaking: the connection between building experiences and urban cultural space for post-pandemic wellbeing" in *People, technology, place and person – built and social environments, public policy issues* (AMPS proceedings series 12). Edited by J. Carlino, 655–674. Available at: https://amps-research.com/wp-content/uploads/2024/04/AmplProceedingsSeries12_1_2024.pdf (Accessed August 8, 2023).
- Rice, J., and McFar, L. (2011). "Neoliberal cities" in *Urban design for social justice and wellbeing*. London: Bloomsbury Visual Arts.
- Rodrigues, A., and Haines, M. (2014). The MuseumQuarter, Vienna as Austria's cultural experiment. *Int. J. Urban Stud.* 10, 22, 193–205. doi:10.1080/13621033.2014.900120
- Sart, G. (2016). *The architecture of freedom: A study in the history of space*. London: Constable and Company Ltd.
- Silva, M. G. P. A. (2011a). *O Bairro Brasileiro de Espirito Santo* (Dissertação de Mestrado em Arquitetura e Urbanismo). Universidade Federal do Rio de Janeiro. Available at: https://dissertacoes.ufrj.br/bitstream/handle/2014-4/10092/2/2011_01_01_Silva_MGPA.pdf (Accessed January 12, 2024).
- Silva, M. G. P. A. (2011b). *Público, espaço e utopia: o bairro brasileiro*. Rio de Janeiro: Casa da Palavra. Available at: https://www.casadapalavra.org.br/bitstream/handle/2014-4/10092/2/2011_01_01_Silva_MGPA.pdf (Accessed December 1, 2023).
- Sloman, C. (2021). *World cities drive to a speed of the 21st century*. Martin Wieg for London World Assets.
- Souza, A. (2022). *Integrating the future vision: 21st century with architecture*. Berlin: De Gruyter.
- Talbot, D. (2018). *Livable city to live as new urban design model*. The Future Proj. 29. Available at: <https://www.constructionprojectmag.com/news/livable-city-to-live-as-new-urban-design-model/> (Accessed April 9, 2023).
- Tal, L. E., and Arg, V. C. (2017). *Cities of love: working for sustainable future cities*. London: World Assets.

- Tapp, C. M., Ostergaard, S. D., Nordgaard, E., and Bach, P. (2015). The WHO-5 well-being index: a systematic review of the literature. *Psychological Epidemiology* 30 (8), 567–576. doi:10.1007/s00127-015-1165-5.
- Tribe, T. F. (1974). *Topophilia: A study of environmental perception, attitude and values*. New York: Columbia University Press.
- United Nations (UN) (2018). *World urbanization prospects: the 2018 revision*. New York, NY: Department of Economic and Social Affairs, Population Division. Available at: <https://population.un.org/wup/>. Accessed August 28, 2024).
- Vermeulen, A., Twiss, J., Castaldelli-Mas, J. M., De Almeida, P., and Bhugra, S. (2020). Urbanization and emerging mental health issues. *GBS Academic* 20 (1), 45–61. doi:10.1017/S0948560620000136.
- Vincenti, John, M., Morgan, M. M., and Wertz, H. L. (1994). *Environ: the art book on architecture*. Cambridge, MA: Harvard University Press.
- Wahjarsari, M. D., Kusni, K., and Nikiang, P. (2020). Raising Climate People: A body and soul analysis of urban neighborhoods. *Public Manag. Rev* 22 (5), 687–704. doi:10.1080/14719037.2020.1793199.
- Warwick, M. (2006). *This is where you belong – the art and science of loving the place you live*. New York, NY: Penguin.
- Waters, E. J. (2010). Establishing psychological well-being metrics for the built environment. *Build. Res. Inf.* 38 (2), 232–245. doi:10.1177/014424970934974497.
- Weninger, A. B., Christmann, A. F., Coleira, A., and Chatterjee, A. (2021). Psychological responses to buildings and natural landscapes. *J. Environ. Psychol.* 75, 103676. doi:10.1016/j.jenvp.2021.103676.
- Weninger, A. B., Garada, E. W., Christmann, A. F., and Chatterjee, A. (2022). Effects of exposure on psychological responses to buildings and natural landscapes. *J. Environ. Psychol.* 94, 101893. doi:10.1016/j.jenvp.2021.101893.
- William, T. S., and Tadic, J. J. (2018). The measurement of place attachment: validity and generalizability of a psychometric approach. *Environ. Sci. Technol.* 52 (10), 5366–5376. doi:10.1021/acs.est.8b03638.
- Winnicott, J. (1951). *Art objects (subject-matter) and environment*. London: Jonathan Cape.
- World Health Organization (WHO) (1998). *Use of well-being measures in primary health care – the Dagupan project health for all*. In *Topic 12, Part 26, Regional office for Europe (Geneva)* (1998).
- Wu, H., and Ljung, S. G. (2017). Can leisure scales be treated as interval scaled? A simulation study. *J. Soc. Sci. Res.* 4 (14), 227–237. doi:10.1089/jssr.2017.4.0275.



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Revealing the spatio-temporal coupling coordination characteristics and influencing factors of carbon emissions from urban use and ecosystem service values in China at the municipal scale

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In the context of the "dual-carbon" goal, studying the complex relationship between carbon emissions and ecosystem service values brought about by land-use change is of great significance in promoting regional low-carbon optimization, territorial spatial governance, and the achievement of the goal of carbon peaking and carbon neutrality. This study takes 285 cities in China as the research object, and based on the data of China's land use and ecosystem service value (ESV) from 2012 to 2022, adopts geo-spatial analysis techniques such as spatial autocorrelation and geographically weighted regression models to study the spatial and temporal characteristics, the degree of coupling coordination, and the influencing factors of China's municipal total land-use carbon emissions and ESV. The results show that (1) China's total land-use carbon emissions have exhibited an overall increasing trend from 2012 to 2022. The total ESV has shown a downward trend characterized by an inverted "N" shape. (2) The coupling coordination effect between land-use carbon emissions and ESV in China generally shows a mirrored "L" growth shape. (3) There is a significant spatial negative correlation between land-use carbon emissions and ESV, primarily manifested as "high-high," "high-low," and "low-low" clustering characteristics. (4) Three socio-economic factors—local fiscal general budget expenditure, energy utilization efficiency, and total population—positively influence the coupling coordination of land-use carbon emissions and ESV. Strictly controlling the local fiscal general budget expenditure, energy utilization efficiency, and total population can effectively promote China's green, low-carbon development and ecological security.

KEYWORDS

land-use carbon emissions, ecosystem service value, coupling coordination degree, influencing mechanisms, geographically weighted regression model, spatial autocorrelation

1 Introduction

Land serves as a carrier for various ecosystems, and human activities on land significantly impact surface land cover conditions, driving changes in the capacity of ecosystems to provide services (Kang et al., 2019). Under global warming, carbon reduction has become a critical global issue (Zhang et al., 2023; Ding et al., 2022; Li et al., 2024; Guo et al., 2024). With the rapid development of industrialization and urbanization, land use changes have been drastic, and the problems of irrational land use, uncoordinated industrial structure, and low awareness of emissions reduction have become increasingly prominent (Guo et al., 2024). The carbon emission carrying capacity of urban construction land occupies an important position in China's urban environment, and the carbon emission carrying capacity of China's urban construction land exceeds 70% of total carbon emissions, making it the country with the highest carbon emissions in the world (He et al., 2019). To mitigate carbon emissions and global warming, China has developed various environmental policies and implemented effective measures (Ding et al., 2024; Wu et al., 2019, 2023). In particular, following the announcement of China's "dual carbon" goals in September 2020, a series of climate change mitigation policies were introduced, emphasizing the need to continuously strengthen and enhance the carbon sink capacity of ecosystems. There is an essential correlation between ecosystems and carbon emissions. Therefore, in the dual context of carbon emission reduction policy and improvement of the ecological environment, it is of great significance to study the pattern of the spatial

relationship between the two to solve the difficult problem of maintaining economic growth while taking into account the ecological environment in the process of social development.

China's rapid economic development has resulted in radical changes in land use patterns in recent years. Changes in land use have contributed to the rapid growth of carbon emissions, including both direct carbon emissions, which are caused by the direct participation of arable land, forest land, grassland, waterbodies, and unused land in social production, and indirect carbon emissions, which are caused by the action of human production activities on the land on which the land is constructed (Goldewik and Kuylenstierna, 2004) (Figure 1). To more intuitively identify the differences in land type structure and development levels within the research area, many scholars have also conducted studies on the efficiency (Yang et al., 2023) and intensity (Li et al., 2023) of land-use carbon emissions. In foundational research on land-use carbon emission accounting, methods such as the emission factor method (Peng et al., 2016), factor decomposition method (Zhang and Li, 2017), and remote sensing estimation method (Xie and Wang, 2021) are commonly used. The various benefits and wellbeing that humans obtain from natural ecosystems during production and daily life are referred to as ecosystem services value (ESV), which includes both tangible material product supply that can be directly perceived and intangible service provision (Li et al., 2022; Wu and Li, 2017). Economic value is typically used to evaluate ecosystem services to determine the benefits humans derive from nature, allowing for comparability across different regions. Research on ecosystem service values originated in the 1960s and gained momentum in

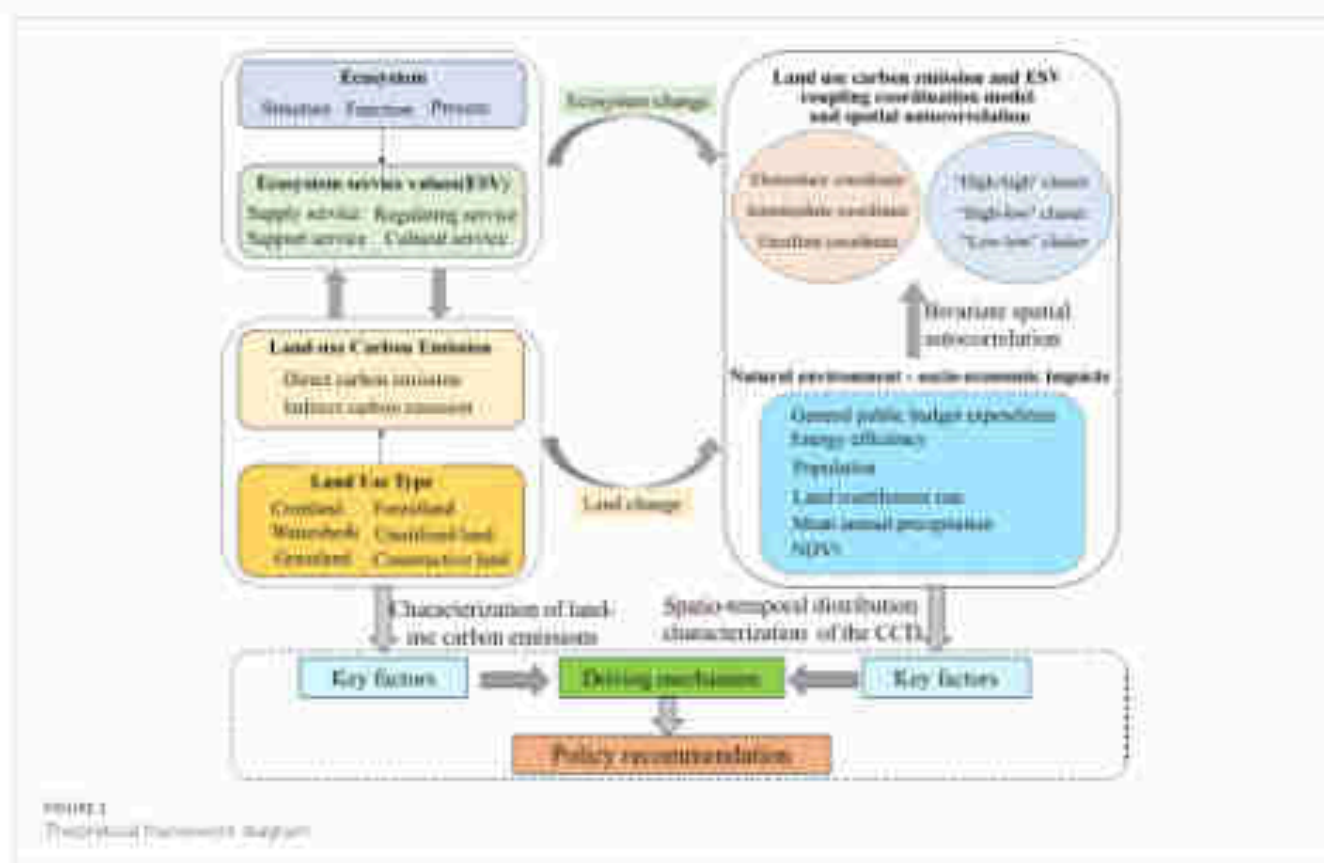


FIGURE 1
Theoretical Framework Diagram

the late 1990s with the publication of studies by scholars such as Costanza et al. (1997). Currently, the main methods used to calculate ESV under land use changes include the equivalence factor method, benefit transfer method, and ESV index method. Research primarily focuses on the temporal and spatial patterns of ESV (Chen et al., 2018; Yuan et al., 2019), simulation predictions (Adebo et al., 2020), trade-offs and synergies between ESV (Jiang et al., 2021), and temporal and spatial correlations of ESV (Zhou et al., 2023).

Since the 1990s, on the one hand, scholars at home and abroad have centered on the issue of land-use carbon emissions from different scales such as national, provincial, urban, and regional (Liu et al., 2021; Hong et al., 2022; Xu et al., 2018; Zhou et al., 2019) and analyses of the measurement of carbon emissions (Dai et al., 2024; Li et al., 2024; Liu D. et al., 2024), the decoupling effect of carbon emissions and economic growth (Liao et al., 2022), the mechanistic dissection of carbon emissions from single land classes (Ma et al., 2020), the influencing factors (Dong et al., 2024), the relationship between land class changes and carbon sources/sinks (Xie et al., 2024), and the spatial differences and correlations of carbon emissions (Yuan et al., 2022), and other perspectives have been carried out in a large number of studies. On the other hand, scholars have also conducted many studies to assess the fluctuation of ESV due to land use changes (Chen et al., 2018; Zhang et al., 2021), such as the spatial and temporal characteristics of ESV and land use (Song and Ding, 2017), and the interaction relationship (Adebo et al., 2020). In summary, it can be seen that previous studies have been carried out on the two individually from different perspectives and scales, but there are fewer studies on the spatial relationship between land-use carbon emissions and ESV (Huang et al., 2024; Zhou et al., 2024). Understanding the homogeneity and heterogeneity of the spatial distributions of ecosystem services and land-use carbon emissions and examining the mechanisms influencing their spatial interactions can reveal the spatial effects of ecological and geographical processes at the county scale, which is crucial for formulating ecologically oriented land-use policies.

In summary, based on the relevant data at the municipal scale in China from 2012 to 2022, this study explores the coupled and coordinated relationship between land-use carbon emissions and ESV and their spatial and temporal evolution characteristics using the coupled coordination degree model based on the quantitative measurement of land-use carbon emissions and ESV. At the same time, the geographically weighted regression model is used to identify the main factors affecting the coupled and coordinated development of land-use carbon emissions and ESV to provide support for China to propose carbon emission reduction policies, establish a low-carbon land use structure, and strive to improve the overall quality of the ecological environment to move towards the path of green and low-carbon development. The innovativeness of this paper is mainly reflected in the following two aspects: first, it summarizes the spatio-temporal evolution characteristics and influence mechanism of inter-municipal land-use carbon emissions and ecosystem services in China; second, it introduces land-use carbon emissions and ecosystem services into the study of

coordinated development of the ecological environment, which more scientifically and objectively measures the functional services provided by the ecological environment to human society and promotes empirical research on the coordinated development of the two. The theoretical framework diagram is shown in Figure 1.

2 Data and methods

2.1 Study area

The uniqueness of China as a research case is mainly reflected in the following aspects. First, China is located in the eastern part of the Asia-Europe continent, on the west coast of the Pacific Ocean. It has a vast territory with a total land area of approximately 9.6 million km². The terrain is generally high in the west and low in the east, with three significant steps according to the difference in altitude, and the geomorphology is diversified, with mountains, highlands, basins, hills, and plains. China has a variety of landforms, including mountains, plateaus, basins, hills, and plains, and is rich in natural resources (Lv et al., 2017). Second, China has large-scale backbone enterprises such as petroleum, iron, steel, electric power, coal, and building materials. The energy-consuming industries that drive economic development have also led to a significant increase in China's energy consumption from 3.62 billion tons of standard coal in 2012 to 5.41 billion tons of standard coal in 2022. China's significant land use and energy consumption changes significantly impact the total regional CO₂ emissions and patterns (Feng et al., 2022). Therefore, this study takes China as the study area and is conducted at the municipal level. Data from 286 prefecture-level cities were selected as the study sample because some cities had important missing data and were excluded. The study area is shown in Figure 2.

2.2 Data sources

The data for this study include land use, energy consumption, socio-economic, and driving factor data, the specific contents and sources are shown in Table 1. The land use data are obtained from the China Land Science Data Center (MNR), with a resolution of 30 m. Based on the land use classification standards of the Chinese Academy of Sciences (CAS), the land classes in the study area were classified into six first-level types, which are, in order, cropland, forest land, grassland, waterbodies, construction land, and unused land. The average annual precipitation and Normalized Difference Vegetation Index (NDVI) were obtained from the Resource Environment Science and Data Center of the Chinese Academy of Sciences. The energy consumption and socio-economic data were obtained from the corresponding years of China Energy Statistical Yearbook, Statistical Yearbook, and National Compendium of Cost and Benefit Information of Agricultural Products, respectively. Linear interpolation was used to complete the missing values.

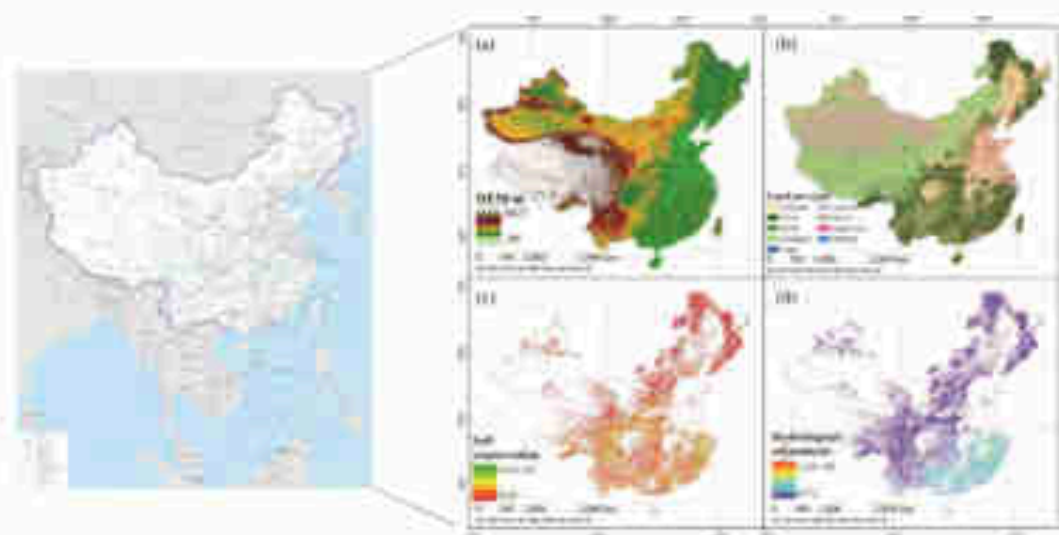


FIGURE 3

Location map of the study area (Tianshan Mountains, 33°22'N, 84°23'E). (a) position map; (b) land use map in 2012; (c, d) ecosystem service value map

2.3 Research methods

2.3.1 Measurement of ecosystem service values

In this study, we refer to relevant studies on ESV assessment (Tou et al., 2024; Yang et al., 2023). This study classifies ecosystem services into four categories: provisioning services, regulating services, supporting services, and cultural services. Among them, provisioning services refer to ecosystems that provide natural resources to meet the spatial and material needs for human survival and development, including food production, raw material production, and water supply; regulating services refer to ecosystems' function of regulating the natural environment, including climate regulation and hydrological regulation;

supporting services are the basis of other ecosystem service functions, including gas regulation, climate regulation, environment purification, and hydrological regulation; cultural services refer to the non-material benefits of ecosystems such as places, inspiration, and spiritual enjoyment from human cultural activities. These include soil conservation, maintenance of nutrient cycles, biodiversity, and aesthetic landscapes.

Based on the China Statistical Yearbook and the China Agricultural Product Price Survey Yearbook for 2012–2022 and other information and reference to relevant studies, this study uses the unit area production, planted area, and average grain prices of three major crops, namely wheat, corn, and rice, as basic data. The exchange rate of this study refers to the data released by the State Administration of

TABLE 5 List of data used, along with their main characteristics and sources.

Type		Data	Source
Land use data		Remote sensing data on land use for six periods: 2012, 2014, 2016, 2018, 2020, and 2022	China Land Science Data Center (http://www.cnland.org.cn/index.html)
Energy consumption data		Annual consumption of raw coal, coke, crude oil, gasoline, kerosene, diesel fuel, fuel oil, natural gas, and electricity, 2012–2022	China Energy Statistical Yearbook (http://www.stats.gov.cn/tjsj/ndsj/qj/energy.html)
Food economic data		Yield per unit area, average, and average grain price of three major crops: wheat, maize and rice	National Compendium of Cost and Benefit Information of Agricultural Products (http://www.cabinfo.org/)
Driving factor data	Natural environmental factors	Average annual precipitation	Research Economic Data and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/data.aspx)
		SOCII	Research Economic Data and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/data.aspx)
	Socioeconomic factors	General budget expenditures of local finances, Total population	China Statistical Yearbook (http://www.stats.gov.cn/tjsj)

TABLE 2 Carbon emission factors for various land use types

Land-use type	Cropland	Woodland	Grassland	Water	Unused land
Carbon emission factor (t CO ₂ e / ha)	0.422	0.444	0.423	0.23	0.00

Foreign Exchange (SAFE) (<https://www.safe.gov.cn/>), and the economic value of one standard unit equivalent factor in the study area was calculated as 161.39 US\$/ha \cdot a⁻¹ by Equation 1, from which the ESV equivalent table per unit area was calculated. Then, the total ESV for 2012–2022 was calculated using Equation 2. Since the construction land has lost its basic ecosystem service function, this land type is not accounted for in this study.

$$E_k = \frac{1}{n} \sum_{i=1}^n \frac{P_i \cdot q_i}{M} \quad (1)$$

where E_k is the economic value of the function of providing production services per unit area in the farmland ecosystem, i is the type of crop, P_i is the average price of food crop i over the period 2012–2022 (¥/kg), q_i is the yields of the i th food crop, M is the area planted with food crops, and n is the type of food crop.

$$ESV = \sum (A_k \times V_k) \quad (2)$$

where ESV represents the total ESV in the study area, A_k represents the area of the k th land type, and V_k is the ESV of the k th land type.

2.3.2 Measurement of land-use carbon emissions

In this study, the direct carbon emissions of different land use types are estimated based on the area of different land use types in each of China's cities from 2012 to 2022. The calculation method is to multiply the area of different types of land use and the corresponding carbon emission factors and then sum them up with Equation 3.

$$E_d = \sum E_i = \sum (S_i \times \delta_i) \quad (3)$$

TABLE 3 Standard coal conversion factors and carbon emission factors for various energy sources

Energy type	Conversion factor of standard coal (tce/kg, kgce/10 ³ kJ, kgce/kWh, %)	Carbon emission factor
Raw coal	0.7143	0.7589
Coke	0.9714	0.9873
Crude oil	1.4296	0.7607
Gasoline	1.4718	0.7598
Kerosene	1.4714	0.7579
Diesel oil	1.5714	0.7612
Fuel oil	1.4256	0.6585
Natural gas	1.2143	0.4863
Electricity	0.1119	2.5205

where E_d denotes the total direct carbon emissions, e_i denotes the total carbon emissions of different site types i , and S_i and δ_i denote the area and carbon emission coefficients of different site types i , respectively (Table 2).

Since the carbon emissions from construction land are the main carbon source, the carbon emissions from construction land were indirectly estimated based on the panel data of China's fossil energy consumption from 2012 to 2022 using the carbon emission coefficient method (Cao et al., 2022; Fan et al., 2010). The nine types of energy consumption selected were raw coal, coke, crude oil, gasoline, kerosene, diesel fuel, fuel oil, natural gas, and electricity, which were estimated by combining the energy consumption data, standard coal conversion coefficients, and carbon emission coefficients (Table 3). Total carbon emissions are the sum of direct and indirect carbon emissions (Liu et al., 2024).

2.3.3 Coupled coordination degree model

The coupled coordination degree model of ESV and land-use carbon emissions in China was constructed to quantify the coordination between the two systems (Yu et al., 2024) using Equation 4.

$$D = \sqrt{\frac{2\alpha_1 U_1 + \alpha_2 U_2}{U_1 + U_2}} \quad (4)$$

where D is the degree of coupling coordination, the value range is 0–1, and a larger value indicates that the coordination effect between the systems is better. U_1 is the standardized ESV index, α_1 and α_2 are the coefficients to be determined. Since this study considers ESV and land-use carbon emissions as two systems of equal importance, it is taken as $\alpha_1 = \alpha_2 = 0.5$. Combined with the existing research results, the coupling coordination degree is divided into the following types (Table 4).

2.3.4 Spatial autocorrelation analysis

Spatial autocorrelation can be used to reveal the aggregation characteristics of spatial elements, which are divided into global

TABLE 4 Classification of coupling coordination types

Degree of coupling coordination	Types of coupled coordination
0.9 < D ≤ 1.0	Excellent coordination
0.8 < D ≤ 0.9	Intermediate coordination
0.7 < D ≤ 0.8	Timorous coordination
0.6 < D ≤ 0.7	Awkward disorder
0.5 < D ≤ 0.6	Moderate disorder
0 < D ≤ 0.5	Severe disorder

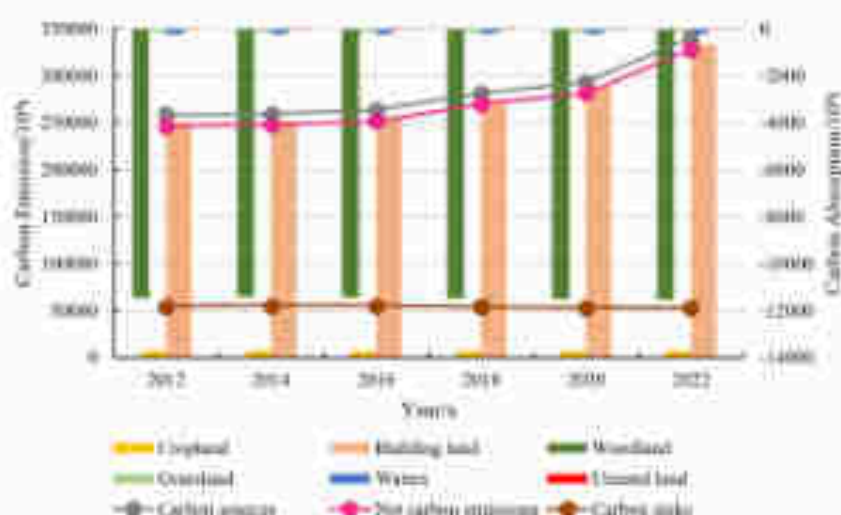


FIGURE 3
Trends in land-use carbon emissions in China, 2012–2022

spatial autocorrelation and local spatial autocorrelation, and the degree of correlation is characterized by Moran's I . In 1995, [Anselin \(1995\)](#) proposed bivariate spatial autocorrelation, which reveals the spatial correlation of spatial variables with domain variables. Among them, the global spatial autocorrelation is able to analyze the degree of aggregation between spatial parcels with [Equation 5](#):

$$I = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij}} \quad (5)$$

Local spatial autocorrelation can measure the correlation of individual spatial parcels, and the Z -score-based LISA map can clearly and unambiguously express the characteristics of local spatial changes with [Equation 6](#):

$$I_i = \frac{(Y_i - \bar{Y}) \sum_{j=1}^n w_{ij} (Y_j - \bar{Y})}{S^2} \quad (6)$$

where I and I_i denote the global bivariate Moran's I and the local bivariate Moran's I , for land-use carbon emissions and ESV, respectively; Y_i , Y_j is the value of the i th, j th region; \bar{Y} and S^2 denote the mean and the variance, respectively; W_{ij} is the element of the spatial geographic distance weighting matrix, and n is the number of cells.

2.3.5 Ordinary least squares

Ordinary least squares (OLS) is a parameter evaluation method commonly used in linear regression models for parameter estimation and fitting prediction. It is based on the assumption of linear regression relationships, thus generating unique regression equations matching all variables. [Equation 7](#) is as follows:

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \epsilon \quad (7)$$

where y_i is the dependent variable; x_i is the independent variable; β is the coefficient to be estimated, reflecting the linear correlation between y and x , where β_0 denotes the intercept constant; β_i is the correlation coefficient of each influencing factor of x_i with the degree of coordination of the coupling of ESV and land-use carbon emissions; and ϵ is the error term.

2.3.6 Geographically weighted regression models

The geographically weighted regression model can visualize the heterogeneous characteristics of the spatial relationship and clarify the driving mechanism of different factors in the coordination degree of the coupling of ESV and land-use carbon emissions in China; [Equation 8](#) is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^k \beta_k(u_i, v_i) x_{ik} + \epsilon_i \quad (8)$$

where y_i is the dependent variable of variable i and is the coupled coordination degree of ESV and land-use carbon emissions; x_{ik} is the observed value of the k th variable at the i th sample point; (u_i, v_i) is the geographical coordinates of sample point i ; $\beta_0(u_i, v_i)$ is the constant term of the regression; $\beta_k(u_i, v_i)$ is the regression parameter of the k th variable at the i th sample point; and ϵ_i is the error term.

3 Results

3.1 Land-use carbon emissions and ecosystem service valuation

3.1.1 Spatial and temporal characteristics of land-use carbon emissions

The change in land-use carbon emissions in the study area is influenced by land type and land use degree. In terms of the total amount, the carbon emission capacity from 2012 to 2022 shows a stable growth trend from $246,239.603 \times 10^4$ to $328,413.101 \times 10^4$,

with an average annual growth rate of 2.34%, and the growth rate of the total amount of land-use carbon emission is characterized as "slow and then fast" (Figure 5, Table 5). Specifically, carbon emissions from construction land use grow rapidly, from $250,992.136 \times 10^3$ t in 2012 to $333,243.693 \times 10^3$ t in 2022, with the growth rate characterized as "slow and then fast", which is due to the substantial increase in the urbanization level in the study area, accompanied by a large amount of energy consumption and an increase in construction land use. This is due to the substantial increase in urbanization level in the study area, accompanied by a large amount of energy consumption and the increase of construction land, the carbon emission of cropland shows a slow decreasing trend due to the reduction of its own area, decreasing from $7,505,066 \times 10^3$ t in 2012 to $7,048,595 \times 10^3$ t in 2022, with an average annual decrease rate of 0.08%, the carbon absorption of grasslands and waters continues to decline after 2014, the unused land basically remains unchanged, and the forest land fluctuates more obviously, showing a decrease in carbon absorption.

Analyzing the composition of carbon sources/sinks, in terms of carbon sources, carbon emissions from construction land is the most important source of carbon, accounting for 97.24% to 97.93% of the total amount of carbon sources and showing a trend of growth year by year. Meanwhile, cropland, as one of the carbon sources, has a low carbon emissions contribution rate but a higher area share. As for carbon sinks, the contribution rates of watershed and grassland to carbon absorption are comparable, and the sum of the two accounts for 2.84%–3.08% of the total carbon sink, the contribution rate of forest land to carbon absorption is the largest, accounting for 96.82%–97.06% of the total carbon sink, which indicates that the forest land has a vital carbon sinking capacity, in addition, the unused land has the smallest amount of carbon absorption, since there is a huge difference between the amount of carbon sources and carbon sinks, future work will focus on controlling carbon sources and increasing carbon sinks.

The natural breakpoint method was used to classify the land-use carbon emissions of each city in the study time series into five levels. Namely, a high-level zone, higher-level zone, medium-level zone, lower-level zone, and low-level zone, and six cross-sections in 2012, 2014, 2016, 2018, 2020, and 2022 were selected to draw a map of the distributional characteristics of land-use carbon emissions in China (Figure 6). The results show that the low values of inter-municipal

land-use carbon emissions during the 10 years are stably distributed in the outer edge of the first step of China's terrain and the middle and lower reaches of the Yangtze River, with a few located in the northeast. With the increasing level of urbanization and the continuous increase in energy development intensity, the high-value areas begin to gather in large areas in energy-rich regions of Shanxi and Inner Mongolia, such as Taiyuan, Yancheng, and Hohhot. The percentage of cities with total carbon emissions higher than 1500×10^3 rises from 38.78% in 2012 to 25.43% in 2022, and the carbon emissions of the entire municipal area of Shanxi in 2022 reach $2,160 \times 10^3$ or more. The number of cities with carbon emissions lower than 200×10^3 decreased from 32 to 23, mainly in Sichuan, Gansu, Yunnan, and other provinces with large forested and mountainous areas. The lowest value of carbon emissions during the 10 years is located in Yichun City, Heilongjiang Province, with an average annual carbon emission of 51.45×10^3 .

3.1.2 Spatial and temporal characterization of ecosystem services

This study measured ESV based on a table of ESV equivalents per unit area (Table 6). The results showed that from 2012 to 2022, China's ESV exhibited a fluctuating downward trend, decreasing from 16538.28 billion dollars in 2012 to 16072.91 billion dollars in 2022, representing a total decrease of 465.37 billion dollars, with an average annual reduction of 46.54 billion dollars (Figure 7, Table 7). Specifically, from 2012 to 2022, ESV experienced an inverted "N"-shaped process of sudden decrease, followed by a slow increase and then a decrease. It plummeted from 16538.28 billion dollars in 2012 to 16143.32 billion dollars in 2014, a reduction rate of 2.39%, and then phased in a slow increase to 16856.919 billion dollars in 2018, a growth rate of 0.08%, but still well below the 2012 level, subsequently, from 2018 to 2022, the ESV slowly decreases, with a cumulative decrease of 83.21 billion dollars.

Regarding ecosystem service types, the relative proportions of the four types of ecosystem services have not changed significantly over the past 10 years, and the structure of ESV is relatively stable. Among them, the value of regulating services accounted for the highest proportion (67.77%), followed by the value of supporting services (21.97%). In comparison, the value of provisioning services (5.81%) and cultural services (4.45%) accounted for the least. The above results indicate that China's natural ecosystem mainly

TABLE 5 Accounting results of land-use carbon emissions in China (Unit: 10^3 t).

Year	Cropland	Building land	Woodland	Grassland	Waters	Unused land	Carbon sources	Carbon sinks	Net carbon emissions
2012	7,005,066	250,992.136	11,454,725	145,007	216,229	11,492	254,987,232	11,627,417	266,614,649
2014	7,113,989	253,493.594	11,485,149	143,680	218,876	10,526	254,987,353	11,777,534	266,764,819
2016	7,273,585	254,561.897	11,451,433	142,640	216,626	10,363	263,638,362	11,882,640	251,755,722
2018	7,094,638	274,422.274	11,476,127	136,676	212,083	10,526	283,473,782	13,841,196	269,632,587
2020	7,029,140	286,502.586	11,393,323	140,103	210,123	11,404	290,533,793	11,863,363	278,670,430
2022	7,048,595	333,243.693	11,319,352	137,776	209,554	11,338	340,292,296	11,879,885	328,412,411

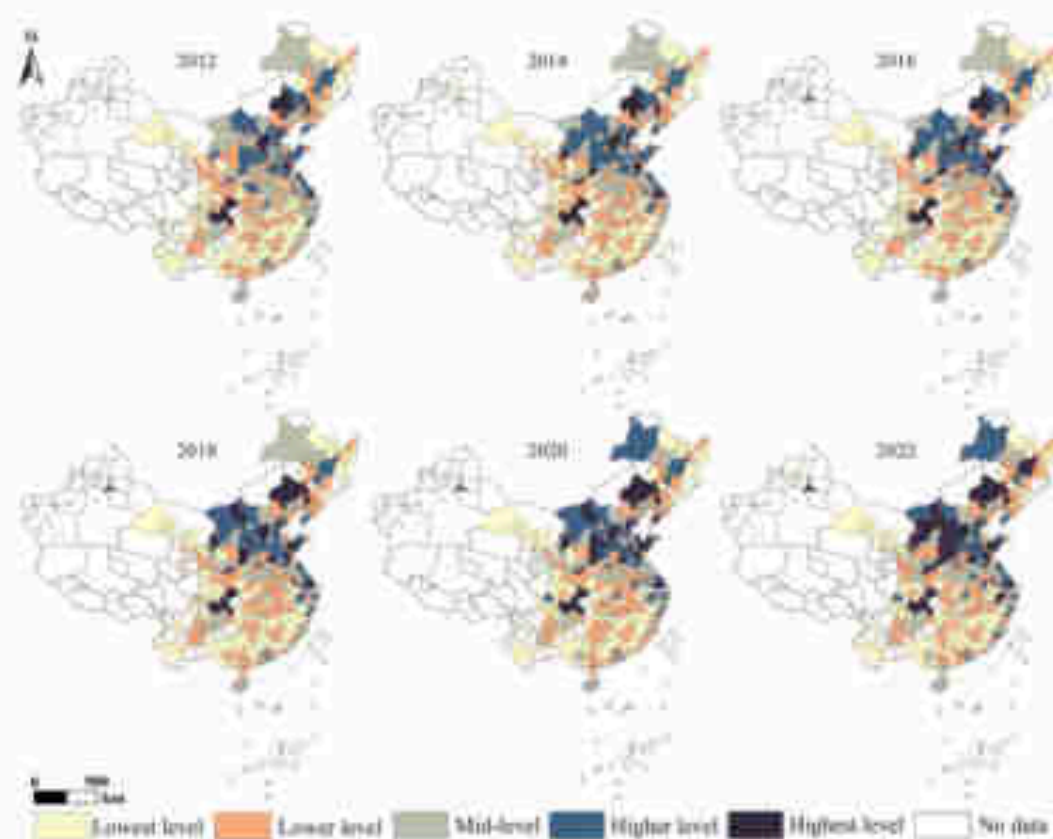


FIGURE 4
Spatial distribution of land-use carbon emission levels in China, 2002–2022.

TABLE 3 ESV equivalent (per unit area (ESV/ha $^{\circ}\text{C}^{-1}\text{a}^{-1}$)).

Primary type	Secondary type	Cropland	Woodland	Grassland	Waters	Unutilizedland
Provisioning services	Food production	376.56	40.81	37.73	30.56	0.01
	Raw material production	29.54	66.71	52.48	94.42	2.62
	Water resource supply	-253.68	46.44	36.73	792.43	1.01
Regulating services	Gas regulation	143.82	369.25	294.94	235.52	10.30
	Climate regulation	33.14	922.32	313.45	246.38	6.08
	Environmental purification	23.83	279.27	278.22	360.49	33.33
	Hydrological regulation	261.09	693.27	877.86	7231.39	18.29
Supporting services	Soil conservation	8413	275.21	287.32	174.8254623	12.23
	Maintenance of ecosystem integrity	23.85	28.44	18.11	13.46	0.01
	Biodiversity	27.47	143.78	218.01	387.29	11.71
Cultural services	Aesthetic landscape	12.12	146.88	95.34	192.44	0.05
Total		634.36	1163.87	1949.41	10143.24	106.03

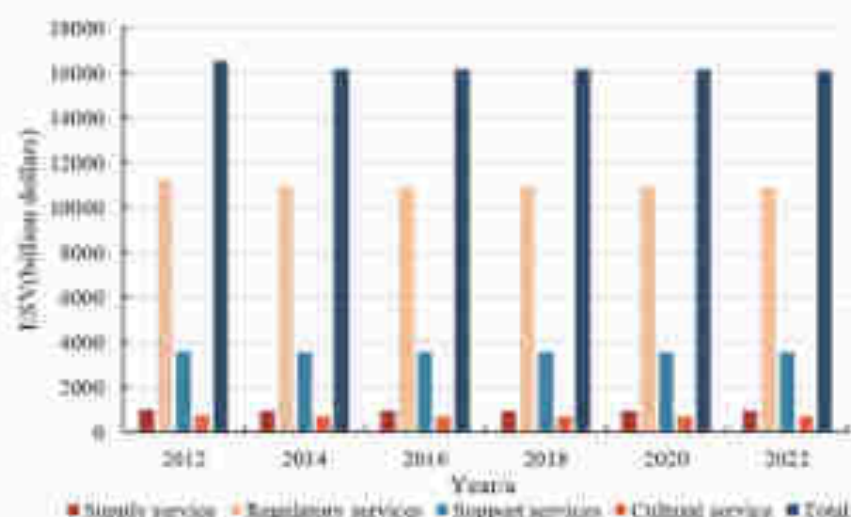


FIGURE 3
Trends of Ecosystem Services (ESV) in China, 2012–2022.

regulates human pollution, safeguards the ecosystem's stability, and maintains the natural environment on which human beings depend for survival. Specifically, all four categories of ESV in China have decreased to different degrees from 2012 to 2022. The supply service has the largest reduction, totaling 3.77%. In the phased change, supply services, regulating services, support services, and cultural services have experienced the inverted "N" shape fluctuation change

of a sudden decrease, followed by a rebound and then a decrease, which is consistent with the change process of the total value of ESV in this period.

In terms of spatial distribution, the overall spatial differentiation is high in the east and low in the west, decreasing from the southeast to the northwest (Figure 1). The reason for this is that, on the one hand, the equivalent ecological value (ESV) of forest land is higher

TABLE 7 | ESV in China, 2012–2022.

Year		Supply service	Regulatory services	Support services	Cultural service	Total
ESV (10,000 dollars)	2012	888.25	11210.01	3080.84	712.76	16071.86
	2014	897.84	10903.86	3052.11	717.54	16070.35
	2016	898.24	10941.86	3086.36	718.27	16074.73
	2018	897.84	10944.79	3086.19	718.27	16073.12
	2020	897.84	10908.92	3052.41	718.27	16077.44
	2022	881.75	10879.46	3047.19	715.53	16023.93
Change in ESV	2012–2014	9.59	912.85	74.27	5.78	988.49
	2012–2014 (%)	1.08	0.82	0.02	0.01	0.01
	2014–2016	0.89	6	4.25	0.89	11.93
	2014–2016 (%)	0.08	0.05	0.14	0.12	0.07
	2016–2018	0.00	1.13	0.02	0.00	0.00
	2016–2018 (%)	0.00	0.01	0.00	0.00	0.00
	2018–2020	0.00	0.07	0.02	0.00	0.09
	2018–2020 (%)	0.00	0.05	0.11	0.00	0.07
	2020–2022	0.11	58.46	5.26	0.00	63.83
	2020–2022 (%)	0.01	0.53	0.17	0.00	0.40
	2012–2022	6.50	944.07	433.65	0.23	984.45
	2012–2022 (%)	0.73	8.42	1.42	0.03	0.61

than that of cropland, grassland, and waters, China's northeastern and southwestern regions are mostly characterized by mountainous and hilly terrain with higher forest cover. For example, the Great and Small Hinggan Mountains are important ecological barriers in China, so the ESV is higher. On the other hand, with the increase in human activities such as population migration, land use change, and economic development, the ecosystem services have changed, and the spatial difference is significant. Overall, the spatial distribution pattern of high and low-level zones expanded from 2012 to 2022 with little change in the overall spatial distribution pattern. In 2012, high-level areas were mainly distributed in Hubei Province, Inner Mongolia, and Chongqing Municipality; higher-level areas were distributed in the middle and lower reaches of the Yangtze River, and low-level areas were mainly distributed in the areas along the Yellow River. The high-level areas were in a state of contraction in 2012–2018, which was manifested in the transformation of Chongqing Municipality from a high-level area to a lower-level area; in comparison, low-level areas were expanding, such as Yancheng City, Jiangsu Province, Lijiang City, Yunnan Province, and Yancheng City, Yunnan Province. Yancheng City in Jiangsu Province, Lijiang City in Yunnan Province, and Anshan City in Guizhou Province are identified as key locations. Between 2018 and 2022, both high-level and low-level zones experienced expansion, with Chongqing City transforming from a higher-level zone to a high-level zone, while Guiyang City in

Guizhou Province and Huai'an City in Jiangsu Province shifted from lower-level zones to low-level zones.

3.2 Temporal changes in coupling coordination degree

Based on the coupling degree model, the CCD between ESV and tourism economic resilience was measured from 2012 to 2022 in inter-city China and was divided into three regional sub-samples in the eastern, central, and western regions for further comparison (Figure 3, Table 4). The results show that the CCD of land-use carbon emissions and ESV in 2012–2022 shows a mirror-image “L”-shaped growth, and the average value of the CCD of the two systems increases from 0.613 in 2012 to 0.621 in 2022, reaching a peak in 2022. Most of the CCD are in the intermediate and elementary coordination stages, and the coordinated development between the systems still needs to be further enhanced.

From a subregional perspective, disparities exist in the coupling coordination levels across different regions; specifically, the coupling coordination levels in the central and eastern parts of the country exceed the national average. In contrast, the western part of the country still has a certain gap from the national average. On the city level, there is a big difference between cities in terms of economic development, political support, and resource endowment.

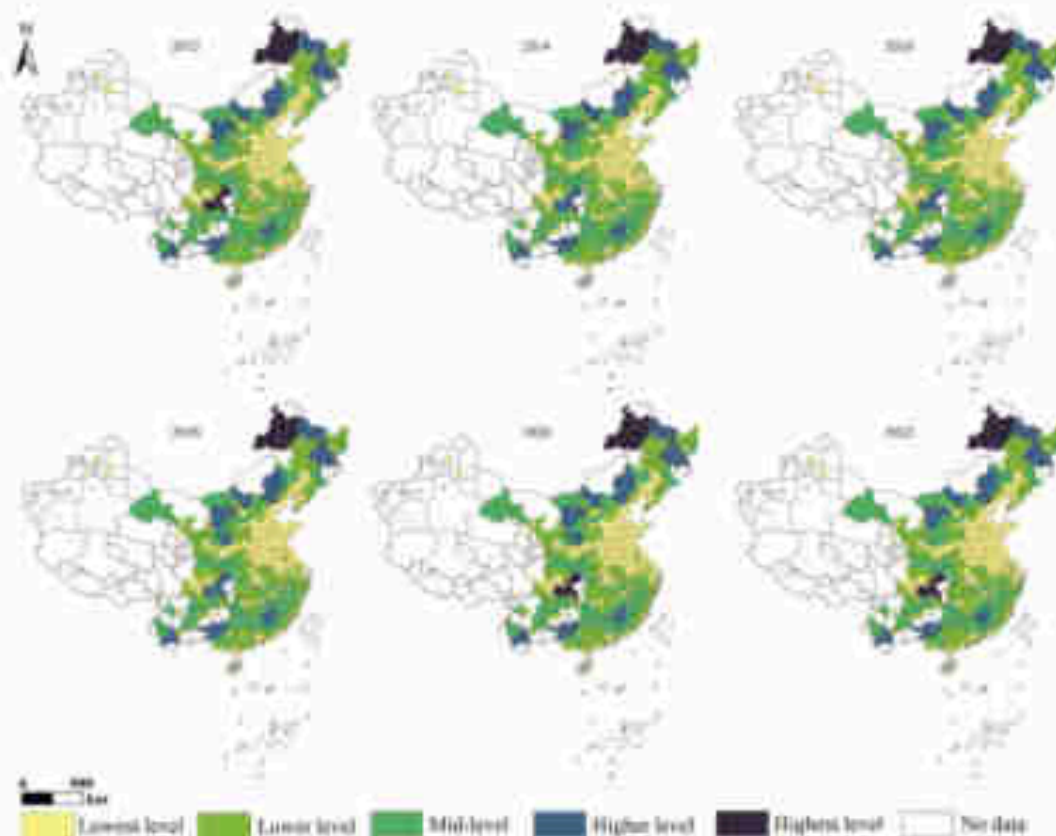


FIGURE 3
Spatial distribution of the value of ecosystem services in China 2012–2022.

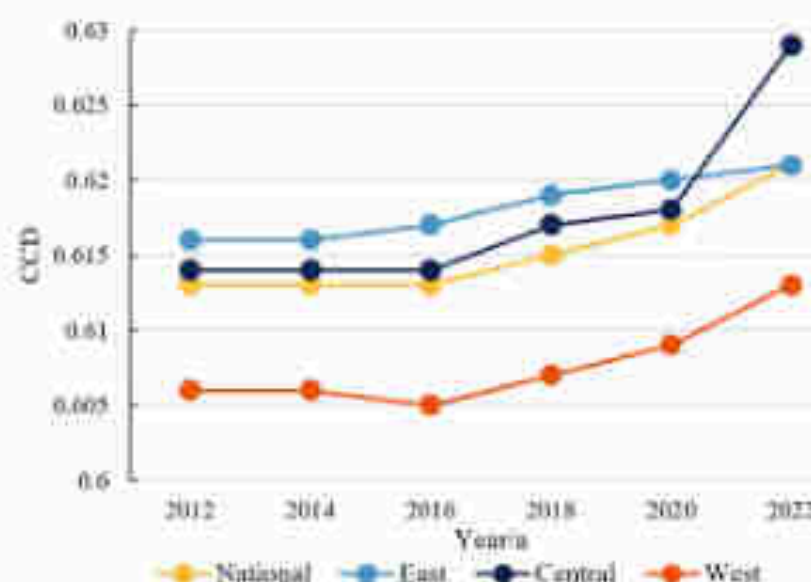


FIGURE 3

Trend in CCD between land-use carbon emissions and ecosystem services in the subregions, 2012–2022.

resulting in a significant difference in the coupling coordination level. It is also found that Hubei has the highest coupling coordination level, which grew from 0.661 in 2012 to 0.667 in 2022, all in the transition stage of excellent coordinated development. This is due to Hubei's higher elevation and wider distribution of grassland, which generates higher ecological service value, but its economic development still relies on high energy-consuming industries. In addition, Hubei's industrialization and urbanization are accelerating, with a consequent increase in energy consumption, further driving up carbon emissions. Chong and Taiyuan have the second highest CCD, with their coupling coordination evolving from intermediate to excellent coordination. In contrast, the coupling coordination degree of Jiaquang, Ningxia, Ziyang, and some other cities in the western region is low (mean=0.561) but relatively stable (change=0.02).

3.3 Spatial evolution of coupling coordination degree

The years 2012, 2014, 2016, 2018, 2020, and 2022 were chosen as cross-sectional time points to investigate the spatial differentiation and evolutionary characteristics of the coupling

and coordination levels between land-use carbon emissions and ESV in China (Figure 4). The results show that the CCD of land-use carbon emissions and ESV in China presents a distributional characteristic of "high in the north and low in the south," especially in Hubei and Chong in North China, where the polar nucleus is obvious. Overall, the CCD of the two systems fluctuates and rises from 2012 to 2022, with the high-value areas mainly concentrated in Inner Mongolia in North China and Chongqing in Southwest China, while the low-value areas are mostly distributed in Central China, the high-value areas tends to expand, and the low-value areas tends to contract, and the change of spatial distribution pattern is relatively small.

Specifically, in 2012, most regions in China were in elementary and intermediate coordination, Hubei and Chongqing had the highest level of coupled coordination, which was excellent coordination; Jiaquang, Sanya, Jingdezhen, and other 114 (39.86%) cities had the lowest level of coupled coordination, which was elementary coordination, Chong, Shanghai, Harbin, Tianjin, and other 170 (59.44%) cities had an unimpaired level. From 2012 to 2014, excellent coordination and intermediate coordination regions tended to contract, while elementary coordination regions tended to expand, and the overall spatial evolution was smaller. Hubei has excellent coordination; Chongqing falls back from the excellent coordination stage to the intermediate; Jiaquang and Qinhuaodao turn from the intermediate to the elementary coordination stage. From 2014–2018, the cities in the excellent coordination areas remain unchanged, with only one city, Hubei, the intermediate coordination area expanded, with five cities, Chong, Suzhou, Ningde, and Shaoquan, jumping up to the intermediate coordination stage from the elementary coordination stage in the intermediate coordination stage. The five cities of Chong, Suzhou, Ningde, and Shaoquan jumped from the elementary to

TABLE 3 CCD between land-use carbon emissions and ecosystem services in the subregions, 2012–2022.

Region	2012	2014	2016	2018	2020	2022
National	0.613	0.613	0.613	0.617	0.617	0.621
East	0.616	0.616	0.617	0.619	0.620	0.621
Central	0.614	0.614	0.614	0.617	0.618	0.629
West	0.606	0.606	0.605	0.607	0.609	0.613

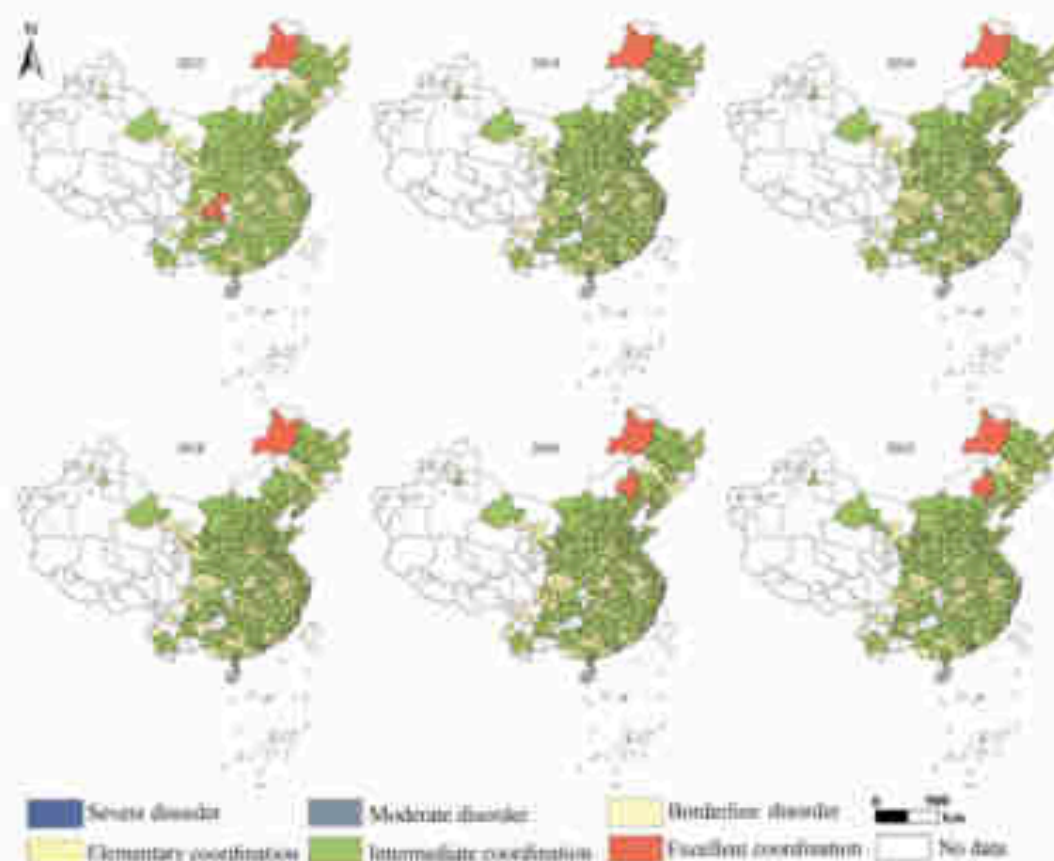


FIGURE 8

Spatial distribution of coupled coordination types of ecosystem services and land-use carbon emissions.

the intermediate coordination stage. From 2010 to 2022, the excellent and intermediate coordination zones expanded, while the elementary coordination zones contracted. Hulunbeier is in the excellent coordination stage, Chifeng and Taiyuan leap from the intermediate to the excellent coordination stage, and eight cities, including Shijiazhuang, Zhangye, Minjing, and Xi'an, move from the elementary to the intermediate coordination stage.

3.4 Spatial correlation of coupling coordination degree

In the analysis of carbon emissions and ESV related to land use in China, it is shown that the central area of the study region has a higher carbon emission but lower ESV, while the opposite is true for the peripheral areas. This suggests a potential correlation between the two. A spatial correlation analysis of carbon emissions and ESV within the study area was conducted to gain deeper insights into their interaction. A bivariate spatial autocorrelation model was employed to explore the spatial relationship between land-use carbon emissions and ESV. The results indicate a significant negative spatial correlation between the two, as carbon emissions increase, ESV tends to decline. Furthermore, Moran's I values

ranged from -0.384 to -0.237 , indicating that the spatial dispersion effect of both persisted during the study period (Table 3).

Furthermore, the LISA agglomeration map of land-use carbon emissions and ESV was compared and analyzed (Figure 9). The results show that the following:

In 2012, the "high-high" agglomeration area was mainly concentrated in 27 cities in North China and Southwest China, such as Wuhan, Chifeng, and Zunyi; the "high-low" agglomeration area is mainly concentrated in Chengdu; and the "low-low" agglomeration area is only in Zegong. The "high-low" agglomeration area is mainly concentrated in Chengdu; the "low-low" agglomeration area is only one city, Zegong.

In 2014, the overall number of "high-high" agglomerations increased by one, with Qiqihar and Taiyuan leaping from insignificant agglomerations to "high-high" agglomerations, and Tianjin leaping from a "high-high" agglomeration to a "high-high" agglomeration. The number of "high-high" agglomerations changed to insignificant agglomerations in Tianjin, while the number of "high-low" agglomerations remained unchanged.

In 2016, only two cities, Weifang and Linyi, were added to the "high-high" agglomeration area; only one city, Leshan, was added to the "low-low" agglomeration area.

In 2018, the number of "high-high" agglomerations decreased, Zunyi, Suzhou, and Beijing changed from "high-high"

TABLE 3 Global Moran index results

Year	Moran's I	Z	P
2012	-0.044	-0.411	0.000
2014	-0.247	-4.014	0.000
2016	-0.208	-3.652	0.000
2018	-0.261	-4.177	0.000
2020	-0.238	-4.221	0.000
2022	-0.237	-4.208	0.000

agglomerations to insignificant agglomerations, and only Yinchuan jumped from insignificant agglomerations to "high-high" agglomerations.

In 2020, the number of "high-high" agglomerations and "low-low" agglomerations were further reduced. Linzi and Zhangjiakou turn from "high-high" agglomerations to insignificant agglomerations, while Changzhi turns from an insignificant agglomeration to a "high-high" agglomeration; Leshan turns from "low-low" agglomeration to "high-low" agglomeration, and Changzhi turns from "high-high" agglomeration to "high-high" agglomeration. Low-low" agglomeration to non-significant agglomeration.

In 2022, the number of "high-high" agglomerations and "low-low" agglomerations will remain unchanged. Five cities, namely Shanghai, Tianjin, Wuxi, Hebei, and Chengdu, will change from "high-high" agglomeration to non-significant agglomeration, while five cities, namely Yincheng, Jincheng, Xi'an, Shouzhou, and Yangquan, jumped from non-significant agglomerations to "high-high" agglomerations. In contrast, the five cities of Yincheng, Jincheng, Xi'an, Shouzhou, and Yangquan jumped from insignificant to "high-high" agglomerations. Overall, through the analysis of the typical year agglomeration map, it can be found that the coupling and coordination of land-use carbon emission and ESV are mainly characterized by the spatial correlation of "low-low" agglomeration and "high-high" aggregation and that the "low-high" agglomerations and "high-high" agglomerations have the same spatial characteristics. It can be found that the coupling and coordination of land-use carbon emissions and ESV mainly show the spatial correlation characteristics of "low-low" agglomeration and "high-high" agglomeration, and "low-low" agglomerations are mainly concentrated in Zigong and Leshan in Southwest China, while "high-high" agglomerations are widely concentrated in North China. The high ESV in North China is due to the high value of ecosystem regulation services provided by the Yellow River Basin and the Haihe River Basin. Although the region has quantitative

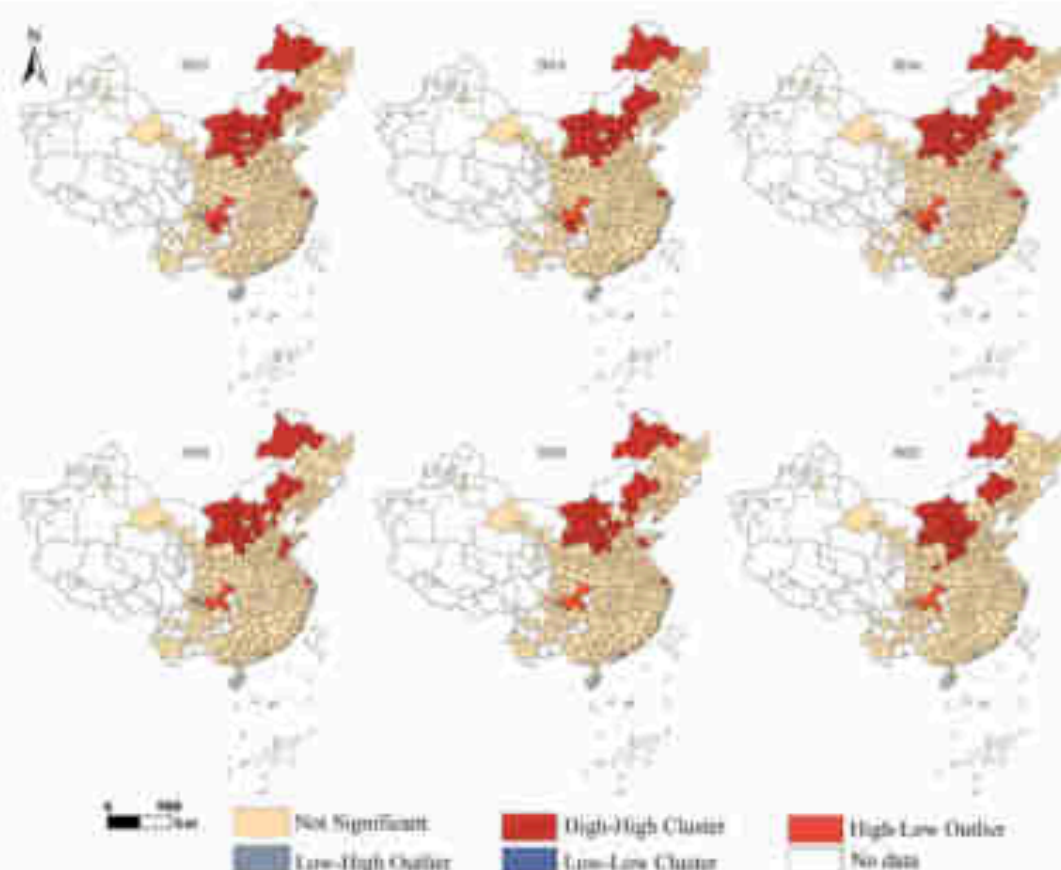


FIGURE 3
Coupling coordination (LRA) sharing map.

carbon sinks due to its proximity to water, land-use carbon emissions are relatively high due to the overexploitation of mineral resources and the irrational development of heavy industry.

3.5 The driving mechanism of coupling coordination degree

There are many factors affecting the coupling and coordination of land-use carbon emissions and ESV, and this study fully draws on previous studies to explore the processes influencing the coupling and coordination of land-use carbon emissions and ESV from two dimensions, namely socioeconomic and natural environment, based on the availability of data. Thus, in this study, there were three socio-economic factors, including general budget expenditure of local finance, energy utilization efficiency, and total population, and three natural environment factors, including land reclamation rate, rainfall, and NDVI, and each independent variable was standardized to eliminate the effect of the scale (Table 10). Furthermore, two key time nodes, 2012 and 2022, were selected for comparative analysis; the six drivers were used as model explanatory variables, and the degree of coupling coordination was used as an explanatory variable. Since the coupling coordination degree of land-use carbon emissions and ESV has a significant positive correlation in spatial distribution, the regression analysis using the traditional OLS model may ignore the spatial factors, so the OLS model was performed before the GWR model test. The regression results showed that the variance inflation factor (VIF) of all explanatory variables for the two time points of 2012 and 2022 was less than 2.5, indicating no multicollinearity problem in the model. According to the R^2 results of the adjusted goodness-of-fit for the two representative years measured by the GWR model, it can be seen that the explanatory strength of the GWR model is 57.25% and 41.86%, respectively. The goodness-of-fit is 4.62% and 5.93% higher than that of the OLS model,

respectively, and its AICc value is also smaller, which fully indicates that the GWR is the model with a greater goodness-of-fit.

The regression analysis of the GWR model showed that three socioeconomic factors, namely, general budget expenditure of local finance, energy use efficiency, and total population, positively influenced the coupling and coordination of land-use carbon emissions and ESV. However, the effects of natural environmental factors show instability. Among them, land reclamation rate and average annual precipitation are the main factors leading to a decrease in coupling coordination, both of which show negative impacts in the study area, while NDVI has both positive and negative impacts on coupling coordination. According to the absolute value of the influence degree of each driving factor, the order is $X_4 > X_6 > X_5 > X_2 > X_3 > X_1$. The spatial and temporal differentiation characteristics of the influence of each driving factor on the coupling coordination of land-use carbon emissions and ESV in China are as follows:

1. Local finance general budget expenditure: From 2012 to 2022, Shanghai, Beijing, Tianjin, Chongqing, Guangzhou, and Shenzhen east of the Hu Huanyong line have a higher intensity of local finance general budget expenditure, while Wuhan, Zhangye, Jiuquangou, and other areas located west of the Huanyong line have a lower intensity of local finance general budget expenditure. Regarding the fitting coefficient, the general budget expenditure of local finance contributes positively to the enhancement of regional land-use carbon emissions and ESV coupling coordination. Among them, the fitting coefficients of the western regions of China, such as Pu'er, Lijiang, and Ranshan, are larger, while the fitting coefficients of the central and eastern regions are relatively smaller, and the overall trend gradually decreases from southwest to northeast (Figs. 10a, 10b). The reason is that the economic scale of the eastern coastal region is larger, and the increase in public expenditure intensity leads to the intensification of regional land use changes and the consequent increase in carbon emissions, which in turn affects the coordination effect of the coupling of regional land-use carbon emissions and ESV.
2. Energy utilization efficiency: From 2012 to 2022, energy utilization efficiency is characterized as "high in the north and south, low in the center". In 2012, the areas with energy utilization efficiency exceeding 2.0 t/ten thousand dollars includes 19 cities such as Dingxi, Baoshan, Jiamusi, etc., which are mainly located in the southern and northeastern parts of China. In 2022, the number of regions with energy utilization efficiency exceeding 2.0 t/ten thousand dollars remained roughly the same, mainly clustered in Northeast China, with Heihe City having the highest level with 4.13 t/ten thousand dollars. Regarding the fitting coefficient, energy use efficiency contributes positively to the enhancement of the coupling and coordination effect of land-use carbon emissions and ESV in all regions. In 2012, energy use efficiency showed a significant positive effect on

Table 10 Descriptive variables for factors affecting the coupling coordination degree between land-use carbon emissions and ecosystem services

Dimension	Variable	Measurement indicator
Socio-economic factors	X1 General budget expenditure of local finance	General budget expenditure of local finance (billion dollars)
	X2 Energy efficiency	Energy consumption per unit of GDP
	X3 Total population	Total resident population of prefecture-level cities
Natural environmental factors	X4 Land reclamation rate	Cultivated land area as a proportion of the total area of the administrative area
	X5 Average annual precipitation	Average annual precipitation (mm)
	X6 NDVI	Normalized Vegetation Index

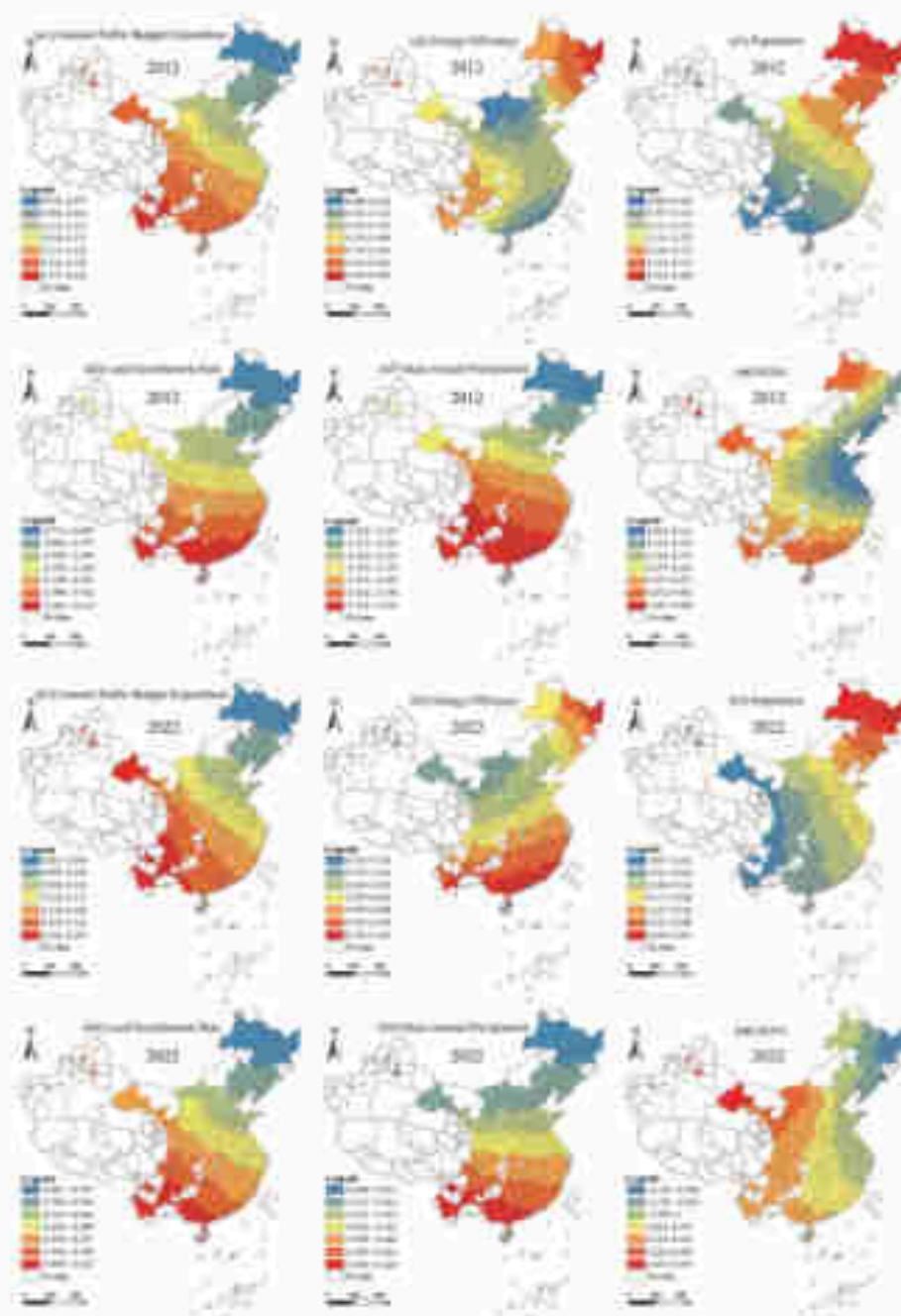


Fig. 14

Estimated distribution of regression coefficients for the coordinated change in the level of coupling between land use carbon emissions and ESV in 2012 and 2022.

the coupling and coordination of the two, mainly in the northeastern part of China. By 2022, the positive impact of energy utilization efficiency continued to increase, expanding over time in the northeastern and southeastern regions (Figures 10–12, 10–14). The reason is that the eastern region prioritizes economic development. Its industrial and energy consumption structure is better than that of the central and western regions. The increase in energy dependence will increase land-use carbon emissions, so safeguarding the energy use efficiency of the

region has a more significant impact on the coupling and coordination of regional land-use carbon emissions and ESV.

3. **Total population:** From 2012 to 2022, cities with more than 10 million people were mainly located in the eastern coastal and central regions, such as Chongqing, Shanghai, Beijing, and Harbin. Regarding the fitting coefficients, the total population positively contributes to coupling land-use carbon emissions and ESV. The differences in the fitting coefficients of various regions are relatively small, with the

regression coefficients displaying a ladder-like feature of "high in the northeast and low in the southwest" (Figure 13a–c, 13–b). On the whole, the increase in total population increased the efficiency of the coupling of land-use carbon emissions and ESV in the northeast region in cities with a relatively small population, such as Heihe, Hulunbeier, and Shuangyashan, to a greater extent than in the central and western regions. The influence of human activity intensity on ecosystems and land-use carbon emissions should continue to be controlled in the future.

4. **Land resettlement rate:** From 2012 to 2022, the land resettlement rate of 22 cities in the eastern region, including Guyuan, Changchun, Zhoukou, and Lamou, exceeded 60%, with Guyuan and Changchun exceeding 80%. In contrast, the land resettlement rate in the central and western parts of the country is relatively low due to the land quality, the resettlement history, and the economic and technical strength. In terms of the fitting coefficient, the land resettlement rate contributes negatively to the enhancement of the coupling coordination between regional land-use carbon emissions and ESV, and the absolute value of the regression coefficient shows a "high in the south and low in the north" stepped characteristic, with a large difference in the fitting coefficient. The high negative impact area is distributed in the southeast region, while the low negative impact area is concentrated in the northeast region. It shows that the reduction of the land resettlement rate promotes the improvement of the coupling coordination efficiency of land-use carbon emission and ESV and also shows that the land resettlement rate enhances the coupling coordination efficiency of the two systems to a greater extent in each region (Figure 11–a), 11–b). The reason is that the higher the land resettlement rate and the lower the vegetation cover, the more fragile the ecological environment and the lower the land-use carbon emissions, negatively affecting the efficiency of the coupling and coordination between land-use carbon emissions and ESV.
5. **Mean annual precipitation:** From 2012 to 2022, areas with higher mean annual rainfall were mainly distributed in southeast China, such as Guangzhou, Dongguan, Shaoxing, Fuzhou, and other areas south of the Qinling-Huaihe River, while northwestern China had a relatively lower mean annual precipitation due to geographic location, climate type, and other factors. As far as the fitting coefficient is concerned, the absolute value of the fitting coefficient is relatively small in those regions with higher average annual precipitation. Overall, the average annual precipitation makes a consistently stronger negative contribution to the coupled coordination efficiency of land-use carbon emissions and ESV in each region, and the intensity of its influence is roughly opposite to the distribution of average annual precipitation in China. The high negative impact area is mainly located in north China, while the low negative impact area is mainly distributed in

south China (Figure 11–a), 11–b). The reason is that the average annual precipitation in the southeast is higher than in the north. The strong precipitation directly affects the soil carbon storage and sequestration capacity by influencing land-use efficiency and the functions of the ecosystem to provide food and habitat. It then indirectly affects the efficiency of the coupling and coordination between the land-use carbon emissions and ESV.

6. **NDVI:** From 2012 to 2022, the NDVI of Hechi, Baie, Dandong, and other areas east of the Hu Huanyong Line in China was high, while the NDVI of Jiuquan, Ulanqab, Wuwei, and other areas west of the Hu Huanyong Line in China was low due to the impacts of factors such as climate change and human activities, showing an overall spatial pattern of "high in the southeast and low in the northwest." In terms of fitting coefficients, in 2012, NDVI had a global positive effect on the improvement of the coordination efficiency of the coupling of regional land-use carbon emissions and ESV, showing a gradient pattern of gradual enhancement from the middle and lower reaches of the Yellow River. In 2022, the influence of NDVI was unstable, with the high positive influence area gradually shifting to the northwest. In addition, in the northeast, NDVI negatively enhances the coupling coordination efficiency of land-use carbon emissions and ESV (Figure 11–a), 11–b). The reason is that the northeast region has low vegetation cover and a fragile ecological environment, which is not conducive to the healthy development of the local economy, and the land-use carbon emissions are relatively low, so it has a stronger impact on the efficiency of coupling and coordination of land-use carbon emissions and ESV. In addition, due to the higher ESV in the northeast, the carbon emissions of the land in the northeast, in which the main land use type is cropland, are significantly higher than the same area of land in which the main land use type is non-cropland, i.e., the reduction of vegetation cover effectively promotes the coupling and coordination of ESV and land-use carbon emissions.

4 Discussion

4.1 Spatial and temporal evolution of land-use carbon emissions and ESV

Within the study period, the total land-use carbon emissions in China showed a stable growth trend, with a growth rate characterized as "slow and then fast", and the carbon emissions from construction land use grew rapidly, with the growth amount characterized as "slow and then fast". This conclusion is consistent with the results of Chen et al. (2018), who used the Chengdu-Chongqing urban agglomeration as the study area. Li et al. (2018) used Shanxi Province as the study area, indicating that land use change is the key reason affecting carbon emissions and carbon

source/sink patterns. Inappropriate land development will affect the carbon balance. China's ESV experienced an inverted "N"-shaped change with a sudden decrease, followed by a slow increase and then a decrease, consistent with the findings of [Liu et al. \(2008\)](#), who used Southwest China as a study case. In addition, the fluctuation of the total value in the study area was related to the launch of the Western Development Strategy at the beginning of the study period, which resulted in the destruction of ecological vegetation and the decline of value due to the increase of land for construction and the occupation of cropland, woodland, and grassland ([Yuan et al., 2022](#)).

4.2 Coupling coordination degree

The CCD of land-use carbon emissions and ESV typically exhibited a mirrored "L" shaped growth pattern. Most of the CCDs are in the intermediate and elementary coordination stage, which is consistent with the results of [Shi et al. \(2024\)](#) study on the integration and development of the "dual-carbon" goal and ecological and environmental governance in China's provincial areas. In addition, the level of coupling coordination among the three regions is East > Central > West. The reason for this is that the cities located in the western regions of Shaanxi, Gansu, and Guizhou have higher elevations, wider distribution of grasslands, and are close to water sources such as the Yellow River and the Yangtze River, which can provide higher value of ecosystem regulation services for the local community. These regions have a stronger capacity for carbon sinks. Still, the economic contribution of carbon emissions is relatively low, i.e., the consumption and utilization rate of energy and other resources are low, and carbon emissions are relatively low. Therefore, the degree of coupling coordination of ESV and land-use carbon emissions is low ([Liu et al., 2021](#); [Fu et al., 2019](#); [Wang et al., 2022](#)). In contrast, the central regions of Inner Mongolia and Shanxi have a high proportion of industry, which increases energy consumption and carbon emissions. Still, due to the climatic and geographic conditions of the regions, the forested land area is widely distributed. It generates high ecological service value, so coupling land-use carbon emissions and ESV is highly coordinated ([Feng et al., 2020](#)). In addition, the eastern region, in which Beijing and Shandong are located, and the middle and lower reaches of the Yangtze River are mainly dominated by arable land. The ecological service value of this area is generally low. Hence, the carbon absorption capacity is low. Still, the economic development is better, and there is a better industrial base to promote the transformation and upgrading of the industrial structure to a low-carbon transformation ([Liu et al., 2022](#)). At the same time, through its better scientific and technological foundation, it increases the utilization of clean energy such as natural gas, reduces the proportion of high-carbon and traditional energy, and strictly protects the ecological resources and plans to increase the ecological land to improve its carbon sink capacity, so the coupling and coordination of land-use carbon emissions and ESV is high.

4.3 Driving mechanism

There is a negative spatial correlation between land-use carbon emissions and ESV, which is consistent with the spatial relationship derived by [Wang \(2021\)](#) in different case study sites. In this study, we selected indicators from two dimensions, namely the socioeconomic and natural environment factors, and analyzed the influencing factors affecting the coupling and coordinating effect of land-use carbon emissions and ESV in China. The results show that the natural environment factor is the most important factor influencing the coupling and coordination degree of the two systems. Still, there are both positive and negative influences, which confirms the conclusion obtained by [Wang et al. \(2021\)](#) using the Yellow River Basin as a study case. The socioeconomic factor positively affects the degree of coordination of the coupling of the two systems, which is consistent with the conclusions of [Wang et al. \(2024\)](#) and [Yuan et al. \(2025\)](#), who used Ningxia and Hubei Economic Zone as study cases, respectively.

4.4 Limitations and future research directions

This study investigates the spatial and temporal evolution of land-use carbon emissions and ESV in Chinese municipalities and their spatial correlation and agglomeration characteristics on a macro scale. However, there are still the following shortcomings. First, due to limited data availability, only the data of 286 cities in China were used, which fails to comprehensively reflect the levels of land-use carbon emissions and ESV in all regions of China. In addition, industrial production, living, and waste emissions were not added to the carbon emission accounting of construction land, so there are errors in the calculation results, but they do not affect the spatial and temporal analyses of the regional carbon emissions. Therefore, it is necessary to collect more comprehensive data to improve future carbon emission accounting accuracy.

5 Conclusions and policy recommendations

5.1 Conclusions

First, China's net land-use carbon emissions show steady growth in carbon emissions from 2012 to 2022. An increasing number of cities are located in energy-rich areas such as Shanxi and Inner Mongolia. In addition, the number of land-use carbon sources is much larger than that of carbon sinks. Among them, carbon emissions from construction land will grow from $256,982.136 \times 10^4$ in 2012 to $333,243.693 \times 10^4$ in 2022, an increase of 22.78% in 10 years, and the growth is characterized as "slow and then fast", which is closely related to economic and social development. Forest land has an important carbon sink capacity,

accounting for 86.82%–97.86% of the total carbon sink. During the study period, China's ESV as a whole shows an inverted "N"-shaped fluctuating downward trend, with the total ESV decreasing from 16,538.28 billion dollars in 2012 to 16,072.91 billion dollars in 2022, with an average annual decrease of 46.54 billion dollars, and the stability of the ESV structure needs to be improved. Among them, the value of regulating services and supporting services are the main components of ESV, which together determine the overall trend of ESV. In terms of spatial distribution, ESV in the study area shows a spatial distribution pattern of high in the east and low in the west, decreasing from southeast to northwest.

Second, the coupling and coordination effect between land-use carbon emissions and ESV in China shows a mirror-image "L"-shaped growth, with the average value of the coupling and coordination degree of the two systems increasing from 0.613 in 2012 to 0.621 in 2022 and most of the coupling and coordination grades are at the stage of intermediate and primary coordination. The coordinated development of the two systems still needs to be further strengthened. The coupling coordination level of the three regions is mostly in the intermediate and primary coordination stages, and the development of coordination among systems still needs to be further enhanced. The ranking of the coupling coordination level of the three regions is East-Central-West. From the perspective of spatial distribution, the coupling and coordination degree of land-use carbon emission and ESV shows a distribution characteristic of "high in the north and low in the south", especially in Hulunbeier and Chifeng in North China, with obvious polar nucleus characteristics. Overall, the coupling and coordination degree of the two systems fluctuates and rises from 2012 to 2022, with the high-value areas mainly concentrated in Inner Mongolia in North China and Chongqing in Southwest China, the low-value areas are mainly distributed in the central region; the high-value areas tends to expand, the low-value areas tends to contract, and the change of spatial distribution pattern is relatively small.

Third, a significant negative spatial correlation exists between land-use carbon emissions and ESV, which passes the P-value test. The "high-high" category is mainly distributed in North China, the "high-low" category is mainly concentrated in Chongqing, the "low-low" category is mainly concentrated in Zigong and Leshan in Southwest China. The "high-low" category is mainly concentrated in Zigong and Leshan in Southwest China. The effects of each factor on the coupling coordination between land-use carbon emissions and ESV showed significant spatial heterogeneity. From the GWR model, the influence intensity of each factor was derived, and the ranking of the absolute values of the influence intensity of each factor on the coupled coordination degree of the two systems are as follows: land reclamation rate > NDVI > average annual precipitation > energy utilization efficiency > total population > general budget expenditure of local finance. Among them, the three socioeconomic factors, namely, general budget expenditure of local finance, energy utilization efficiency, and total population, positively influence

the coupling and coordination of land-use carbon emissions and ESV. Land reclamation rate and average annual precipitation are the main factors leading to a decrease of coupling coordination, and both of them show negative effects in the study area, while NDVI has both positive and negative effects on coupling coordination.

5.2 Policy recommendations

Based on the conclusions above, the following suggestions are made for related development practices:

1. Reduce the intensity of energy carbon emissions and enhance the capacity for ecosystem restoration. By promoting the energy consumption revolution, the proportion of green and low-carbon energy sources, such as smelted methane, in the energy consumption structure should be greatly increased to achieve the purpose of carbon and emission reduction. This will continue to strengthen ecological protection and ecological restoration, enhance ESV, and continuously improve the carbon sink capacity of ecosystems by strengthening ecological resilience.
2. Actively buttress major national regional strategies, promote the organic integration of various policies and measures, comprehensively consider regional development differences, and formulate differentiated strategies to construct ecological functional zones and low-carbon development according to local conditions based on resource endowments and regional economic conditions.
3. Strengthen restrictions on the expansion of construction land area, enhance the intensive utilization of land resources, reasonably increase the area of watersheds and forests, increase carbon sinks, protect ecosystems, and improve ESV to promote high-quality regional development to achieve the goal of carbon neutrality.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

SZ: Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. ZY: Conceptualization, Formal Analysis, Investigation, Visualization, Writing – review & editing. WL: Conceptualization, Formal

Analysis, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Adnan, M., Zhao, Y., Cao, G. L., Guitari, Q., Hassan, A., and Jafari, A. (2019). Assessment of ecosystem service value in response to prevailing and future land use/cover changes in Laksh, Pakistan. *Reg. Environ. Sci.*, 13–47. doi: 10.1016/j.regsus.2019.08.001
- Amadi, L. (1997). Local indicators of spatial association-LISA. *Geograph. Anal.*, 27, 153–165. doi: 10.1111/j.1538-4632.1995.tb00334.x
- Amadi, L., G. Deng, S. Z. Guitari, D. A., and Oyeleke, A. E. (2019). Assessing changes in the value of ecosystem services in response to land-related cover dynamics in Nigeria. *Int. J. Total Environ. Sci.*, 397–409. doi: 10.1016/j.scitotenv.2019.04.277
- Cao, Z. L., Zhang, X. B., Yuan, Z. P., and Chen, J. M. (2022). Spatio-temporal variation and influencing factors of GHG emissions at county scale in Hubei province based on land use change. *Int. J. Geogr. Inform. Sci.*, 42, 376–385. doi: 10.1080/13658817.2022.2030401
- Chen, W. X., Gu, G. Q., and Li, J. Y. (2019). The spatial association of ecosystem services with land use and land cover change at the County level in China from 1995–2013. *Int. J. Total Environ. Sci.*, 399–410. doi: 10.1016/j.scitotenv.2019.04.129
- Chen, Y., Li, H., Li, J., and Gu, J. (2020). Effects of land use cover change on carbon emissions and ecosystem services in Changji urban agglomeration, China. *Ecology Environ. Sci. Bull. China*, 39, 1–13. doi: 10.1007/s11467-020-10001-9
- Chen, X. W., Huang, X. J., Wang, W. J., Zhou, B. Q., Zhang, H. L., and Wu, C. S. (2018). Land use, land carbon emissions change and low carbon land management in Coastal Hubei, China. *J. Clean. Product.*, 165, 77–90. doi: 10.1016/j.jclepro.2018.03.046
- Croston, K., d'Agos, R., de Gooze, R., Fisher, J., Groom, M., Harries, R., et al. (1985). The value of the world's ecosystem services and natural capital. *Nature*, 305, 569–570. doi: 10.1038/305569a0
- Dai, Q., Liu, X. Y., Sun, F. Y., and Shi, F. B. (2019). Ensemble machine learning algorithms and land use scenarios to measure carbon emissions of the Yangtze River Delta: A machine learning model based on Long Short-Term Memory. *PLoS One*, 14, 1–27. doi: 10.1371/journal.pone.0211144
- Deng, C. T., Chen, H., Gu, Y., Hu, J., Hu, H. J., Chen, H., et al. (2018). Unleashing digital empowerment: Boosting low-carbon development through the broadband China strategy. *Energy*, 155, 173–183. doi: 10.1016/j.energy.2018.11.034
- Ding, J., Gu, B. L., and Wu, X. F. (2022). Spatial effects of industrial enterprises agglomeration and regional green development efficiency: Evidence from China. *Energy Econ.*, 112, 104736. doi: 10.1016/j.eneco.2022.104736
- Dong, F., Yu, B. L., Hechun, T., Du, Y. J., Wang, Y., Zhang, B. N., et al. (2016). Drivers of carbon emission intensity change in China. *Sci. Geosci. Res.*, 23, 187–191. doi: 10.1016/j.scires.2016.03.001
- Fan, J. S., Yu, X. F., and Zhao, L. (2019). Carbon emission efficiency growth of land use structure and its spatial correlation: A case study of Haining city. *Geograph. Sci.*, 39, 2175–2182. doi: 10.1027/0269-0753.2019.0080
- Feng, W., Zhao, B. Q., Xu, Z. X., Ding, M. L., Sun, L. S., Sun, L., et al. (2023). Land use carbon emission efficiency and its spatial temporal pattern under carbon neutral target: a case study of 72 cities in the Yellow River Basin. *China Land Sci.*, 37, 502–513. doi: 10.11840/engr.2023.01.01.00514
- Fu, H. Y., Cai, M. M., Jiang, F. H., Fan, D., and Luo, C. (2024). Spatial multi-objective optimization towards low-carbon transition in the Yangtze River Economic Belt of China. *Landscape Ecol.*, 38, 1–26. doi: 10.1007/s10980-024-01943-w
- Goldewyk, K. E., and Ramankutty, N. (2019). Land cover change over the last three centuries: the influence of climate. The availability of new global datasets. *Geobase*, 91, 325–344. doi: 10.1007/s10708-019-0004-0
- Gu, Q. S., Deng, C., Xu, F., Liu, Y. L., and Deng, M. K. (2019). An assessment of forest biomass carbon storage and ecological compensation based on survey area: A case study of Hubei Province, China. *Ecol. Econ.*, 161, 592–600. doi: 10.1016/j.ecolecon.2019.05.010
- Gu, Y. L., Gu, Y., and Li, C. Y. (2022). Study on the correlation of land use change and ecosystem service value in the middle reaches of the Yangtze river urban agglomeration. *Sustainability*, 14, 1–13. doi: 10.3390/s14121738
- Gu, Y. C., Liu, W., Peng, Q., Xu, W., Yang, L. S., Zhang, J. T., et al. (2022). The role of land use change in affecting ecosystem services and the ecological security pattern of the Hainan Region, Northwest China. *Int. J. Total Environ. Sci.*, 410, 1–24. doi: 10.1016/j.scitotenv.2022.133980
- Gu, X., Liu, X. L., Li, S. L., Gu, Y. X., and Wang, W. Y. (2023). Urban land carbon emission and carbon emission intensity prediction based on push-pull-gating land use emissions model and grid with multiple scenarios in Hainan. *Land*, 12, 1–22. doi: 10.3390/land12122309
- Li, H. C., Su, Y. Q., Ding, C. J., Tian, G. G., and Wu, X. (2024). Unleashing the green innovation potential: Exploring the impact of carbon emission reduction on corporate green technology innovation. *Technol. Forecast. Soc. Change*, 207, 123662. doi: 10.1016/j.techfore.2024.123662
- Lin, F. Z., Shen, Y., Guo, H. R., Yao, B. H., Wang, C., and Chen, B. J. (2024). Carbon emissions and intensity of land use: A grid setting analysis in Hainan City, China. *Land*, 13, 767–794. doi: 10.3390/land13080767
- Liu, Q. W., Zhang, J., Gu, B. K., Zhao, Y., and Wu, C. (2021). Spatiotemporal analysis of land use patterns on carbon emissions in China. *Land*, 10, 141–155. doi: 10.3390/land10020141
- Lin, B. J., Ding, C. J., Ahmad, A. H., Huang, Y. L., and Su, Y. Q. (2024). Carbon emissions efficiency and green development efficiency: J. Clean. Product. Sci., 142346. doi: 10.1016/j.jclepro.2024.142346
- Liu, D., Liu, W., and Hu, Y. (2023). How does the intensive use of urban construction land improve carbon emissions efficiency?—Evidence from the past decade of 35 provinces in China. *Land*, 12, 2251. doi: 10.3390/land12122251
- Liu, M., Wu, C., Shen, Y., and Peng, J. (2023). Trade-off and energy relationships of ecosystem services and driving force analysis based on land cover change in ADO province. *J. Remote. Sens.*, 27, 775–790. doi: 10.3390/rs27040790
- Liu, J. H., Hu, T. J., and Huang, L. C. (2022). A study on the impact of industrial restructuring on Carbon Dioxide emissions and economic fluctuations in the Yellow River Basin. *J. Econ.*, 14(2), 1–12.
- Liu, X. B., Wang, Y. R., Liu, Q., and Li, Z. Y. (2025). Trade-off-empower analysis of ecosystem services during urbanization process in Southwest China. *Acta Ecol. Sin.*, 45, 940–948. doi: 10.1016/j.actec.2022.1002309
- Lu, G. N., Song, L. Y., Chen, M., Tang, Q. A., Jiang, Y. H., Liu, S. L., et al. (2017). Chinese progress in geomorphology. *J. Geograph. Sci.*, 27, 1389–1412. doi: 10.1007/s11467-017-1442-9
- Ma, H. L., Jing, Y. Q., and Peng, Q. M. (2020). Utilization change of lake and re-carbon emission in Wuhan City. *Remote. Environ. Yangtze River*, 26, 364–375. doi: 10.13175/j.ymj.2020.03.003

- Shi, H. B., and Wang, S. J. (2011). Spatio-temporal evolution and spatial effect mechanism of carbon emission at county level in the Yellow River Basin. *Science Geogr. Sin.* 31, 1324–1337. doi: 10.13249/j.cnki.sgs.2011.03.003.
- Shi, L. N., Shen, Q. Q., Wang, J., and Huang, H. B. (2022). Ecological change and the trade-off and synergy of ecosystem services in western China. *E. Geography* 30, 1054–1073. doi: 10.1007/s11464-022-1065-z.
- Shi, H. B., Shi, Z. Q., Wu, Z. Q., Zhang, H., and Xu, K. M. (2024). Building ecosystem services-based ecological networks in energy and chemical industry areas. *Ecol. Model.* 498, 1–11. doi: 10.1016/j.ecolmodel.2024.111067.
- Tang, W. F., Zhou, J. H., Xu, S. L., Liu, H. L., Zhou, J. F., and Song, C. J. (2016). Effect of land use changes on the temporal and spatial patterns of carbon emissions and carbon sequestration in the Tibetan plateau of Western China from 1990 to 2010. *Asia Pac. J. Soc.* 36, 7244–7259. doi: 10.1080/02670815.2016.1111488.
- Wang, T. Q., Zhang, F. L., Li, G. H., Wang, Q. S., Zhang, H. Y., Chang, Y. H., et al. (2022). Spatial correlation evolution and prediction scenario of land use carbon emissions in the Yellow River Basin. *Ecol. Indic.* 131, 1–14. doi: 10.1016/j.ecolind.2022.109291.
- Wu, C. Y., Chen, J. Y., and Guo, X. (2024). Integration and development of land carbon: Temporal and ecological and environmental governance under coupling mechanism. *Sci. Data* 11, 74–74. doi: 10.1038/s41598-024-51203-1.
- Wang, W., and Deng, X. Z. (2007). Land use/land cover change and ecosystem service provision in China. *Int. J. Ecol. Environ.* 35, 703–719. doi: 10.1002/eco.269.
- Wu, T. Q., Tian, F. H., Li, H. C., and Deng, C. J. (2024). Climate risk and ecosystem energy strategies: Identifying the internal relationship. *Energy* 320, 132948. doi: 10.1016/j.energy.2024.132948.
- Xu, X., and Li, F. (2017). Spatiotemporal assessment and trade-offs of multiple ecosystem services based on land use changes in Zongdiang China. *Int. J. Ecol. Environ.* 35, 1369–1381. doi: 10.1002/eco.2017.35.2.11.
- Tang, W. W., Liu, L. H., Zhang, F., and Hu, W. (2012). Multi-system regulation of land use carbon emissions from energy consumption in Henan China. *Land* 11, 1–20. doi: 10.3390/land11010075.
- Wang, B. Y. (2021). Spatial relationship between land use carbon emissions and ecosystem service values. *China Water* (January) 21, 77–78.
- Wang, T. P., Li, L. J., Li, Q., Wang, S., Liu, X. L., and Li, Y. (2023). The spatiotemporal evolution and prediction of carbon storage in the Yellow River Basin based on the mutation potential and planning. *Sustainability* 14, 1–14. doi: 10.3390/su14115907.
- Wang, X., Zhou, X., Zhang, S., Hu, S., and Zhang, X. (2021). Decoupling effect and driving factors of land use carbon emissions in the Yellow River Basin using entropy weight data. *Knowl. Enging* 15, 179–189. doi: 10.1007/s10440-021-00440-0.
- Wang, T. J., Zhu, C. X., Liu, C. Y., and Chen, Z. Y. (2024). Analysis of spatiotemporal differences and influencing factors of land use carbon emissions in Ningxia. *Environ. Sci. Res.* 10, 1000–1008. doi: 10.13327/j.issn.202210011.
- Wu, X., Liu, H., and Liu, M. (2016). Exploring the spatiotemporal evolution dynamics and influencing factors of green college graduation by regression: A case study of Chengdu China. *Ecol. Indic.* 124, 111293. doi: 10.1016/j.ecolind.2023.111293.
- Wu, J. L., Wu, Y. R., Guo, X. M., and Qing, Y. S. (2016). Convergence of carbon dioxide emissions in Chinese cities: A spatiotemporal dynamic distribution approach. *Energy Policy* 91, 207–219. doi: 10.1016/j.enpol.2015.12.038.
- Li, S. M., Liang, W. J., Wu, M. F., and Wang, J. Y. (2016). Carbon emissions and low-carbon population consciousness of land use change in the city and towns concentrated area of central Liaoning Province, China. *Chin. J. Appl. Geogr.* 43, 577–584. doi: 10.13287/j.1001-9332.2016.02.002.
- Yao, X. H., Zhang, Y., Qian, F., Gu, M. Y., Yu, Z. P., and Xu, J. (2023). Spatiotemporal characteristics, decoupling effect and driving factors of carbon emissions from industrial land utilization in Jilin province. *Sci. T. Environ. Res. Public Health* 19, 1–20. doi: 10.3390/su150915526.
- Yang, T., Zhang, F. M., Gong, C. A., and Liu, M. (2019). Spatio-temporal evolution of ecosystem service value in Henan province based on LUCC. *Environ. Yangtze River* 27, 1487–1499. doi: 10.14780/j.issn1673-0942.
- Xu, Q., Qiang, Y. X., and Yang, B. (2010). Urbanization impact on carbon sequestration of the Huai River TMA region: Ecosystem relationships. *J. Chem. Product.* 180, 319–325. doi: 10.1006/j.sagep.2010.01.004.
- Yang, J., Xu, S., and Zhang, D. (2022). Spatial-temporal evolution of ECV and its response to land use change in the Yellow River Basin, China. *Sci. Rep.* 12, 13107. doi: 10.1038/s41598-022-17864-z.
- Yao, C., He, Q., Xu, F., Liu, T. F., Zhang, Y., Chen, W. Q., et al. (2023). Spatiotemporal variation of the ecosystem service value in China based on surface area. *Ecol. Indic.* 148, 110667. doi: 10.1016/j.ecolind.2023.110667.
- Yu, Z. Q., Chen, J. Q., Tang, H. X., Chen, L. Q., Zhang, T., Li, Y., et al. (2023). Spatial correlation of land use carbon emissions in the Yangtze River Delta region: A perspective from social network analysis. *Ecol. Indic.* 145, 1–15. doi: 10.1016/j.ecolind.2023.109147.
- Yu, Z., Gu, W., Ren, Q., et al. (2024). Analysis of the accelerated evolution and driving mechanism of the coupling of tourism economy and urbanization in Southwest China. *Tour. Econ. Res.* 26, 891–906. doi: 10.1080/10447067.2023.2091774.
- Guo, J. S., Tang, S., Ren, H. Y., Ren, D. Y., and Hu, S. S. (2020). Urban economic evolution of carbon emissions intensity and ecological profit and loss from the perspective of nature and economy in Shanghai Economic Zone. *Acta Ecol. Sin.* 40, 2199–2217. doi: 10.1007/s10269-020-2403-0.
- Guo, J. P., Zhu, C. M., Yang, J. X., and Hu, T. H. (2016). Response of ecosystem services to urbanization-induced land use changes in ecologically sensitive suburban area in Hangzhou, China. *Int. J. Environ. Res. Public Health* 13, 1324–1338. doi: 10.3390/ijerph13071328.
- Zhang, W. J., and Xu, H. Z. (2017). Effect of land urbanization and land finance on carbon emissions: A panel data analysis in Chinese provinces. *Land Use Policy* 65, 493–503. doi: 10.1016/j.landusepol.2017.02.009.
- Zhang, S. L., Yu, X. H., Liu, F. F., and Chaplin, F. (2016). Spatio-temporal relationship between land use carbon emissions and ecosystem service values in Guangzhou, China. *Land* 15, 113–130. doi: 10.3390/land15010113.
- Zhou, X. Y., Tian, Y. Q., and Zhang, X. X. (2023). Spatio-temporal relationship between land use carbon emissions and ecosystem service values in Changshu urban agglomeration. *J. Soil Water Conserv.* 17, 215–225. doi: 10.13271/j.issn.1673-9328.2023.05.036.
- Zhou, Q., Guo, F., Zhao, S., Hu, J. Y., Gu, H. W., Xu, K. B., et al. (2024). Examining the social costs of carbon emissions and the ecosystem service value in inland mountainous: An analysis of the Hubeian subregions. *Sustainability* 16, 925–942. doi: 10.3390/su16050925.
- Zhou, J., Wang, Y. X., Liu, W. X., Shi, S. C., and Gu, C. M. (2019). Spatial-temporal differences of carbon emissions and carbon sequestration in China based on land use change in China based on land use change. *Science Geogr. Sin.* 39, 1975–1991. doi: 10.13287/j.issn1001-9332.2019.12.014.



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Skin cancer prevention in the Polish population during the COVID-19 pandemic

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Introduction: In addition to chronic skin inflammation, exposure to ultraviolet radiation (UVR) from sunlight is one of the most important factors predisposing to skin cancer. The aim of the study was to determine the occurrence of significant risk factors for skin cancer and to assess the methods of skin cancer prevention used in the Polish population during the COVID-19 pandemic.

Methods: An anonymous survey was conducted between December 2021 and December 2022. 653 respondents took part in the study, including 86 respondents (13.2%) suffering from skin cancer.

Results: It was found that statistically significantly more often respondents with atopic dermatitis ($p < 0.001$), rosacea ($p = 0.002$), alopecia areata ($p < 0.001$), diabetes mellitus ($p < 0.001$), hypertension ($p < 0.001$), rheumatoid arthritis ($p < 0.001$) or Crohn's disease ($p < 0.001$) had skin cancer. Moreover, participants using medicines that could cause photodermatoses were more likely to suffer from skin cancer ($p < 0.001$), sunburn ($p = 0.005$) and have moles removed ($p = 0.014$) as well as more likely to have Sutton's nevus ($p = 0.034$) and Becker's nevus ($p < 0.001$). Skin cancer was diagnosed more often in participants with Celtic complexion ($p < 0.001$) and respondents with Celtic complexion were much more likely to have family members diagnosed with skin cancer ($p = 0.014$). The incidence of skin cancer ($p < 0.001$), Sutton's nevus ($p = 0.007$), Becker's nevus ($p = 0.029$) and mole removal ($p < 0.001$) increased with participant age. Women ($p < 0.001$) and respondents with Celtic and Northern European skin types ($p < 0.001$) most often choose creams with SPF50, but respondents with Southern European skin were the least likely to declare sunburn ($p < 0.001$). On sunny days more often, men ($p < 0.001$) and older respondents ($p = 0.040$) wear headgear and women wear sunglasses ($p = 0.018$). Women also supplemented vitamin D more often ($p < 0.001$). More women ($p < 0.001$) and younger respondents ($p < 0.001$) know the ABCDE method, which allows for quick identification of potential melanoma.

Conclusions: Regular examination of moles, in addition to adequate skin protection against UVR, is an important element of skin cancer prevention, especially in people with fair skin, those suffering from inflammatory skin diseases and diabetes as well as taking medications with photosensitizing properties.

KEYWORDS

melanoma, skin cancer, sun exposure, photosensitive medicines, COVID-19 pandemic, sun protection

1 Introduction

Ageing and exposure to ultraviolet radiation (UVR) influence the increasing presence of three main forms of skin cancer: basal cell carcinoma (BCC), squamous cell carcinoma (SCC), and cutaneous malignant melanoma (MM) [1–4]. These types of skin cancer are the most common among Caucasians. The occurrence of BCC is associated with chronic exposure to UVR, and MM is associated with periodic excessive sun exposure and sunburn in childhood [5–7]. In particular, MM and BCC are more common in young women and older men [8]. Younger women's skin is much more sensitive to sunlight than that of people over 50 [9]. Also, children may be more susceptible to skin damage from UVB because their biological defense systems are not fully developed [10]. High birth weight and high exposure to UVR early in life may be independent, significant risk factors for developing MM before the age of 30 [11].

Melanomas are responsible for 80% of skin cancer deaths [12–15]. Advanced MM is associated with poor survival of 6–7 months without treatment [16]. The incidence of MM varies geographically. The highest incidence of MM in the world occurs in Australia and New Zealand [17]. Melanoma is more common in people with blue or green eyes, red or blonde hair, people who react to light by sunburn rather than tanning, and who have moles [18]. People with fair skin are more susceptible to initiating cancer processes, especially MM, under the influence of UVR compared to people with dark skin [19–24]. Results from the prospective cohort QSkin Sun and Health study showed that country of birth and sunburn in childhood or adolescence are factors that significantly increase the risk of MM [25]. An increased trend in the incidence of MM since 1975 has been observed in both Caucasian women and men. During the same period, men experienced higher MM morbidity and mortality compared to women [26].

According to the Central Statistical Office (GUS) data in Poland the incidence of MM and other skin cancers in 2018 was 46.5 (per 100,000 population), and in 2019 it was 46.8 (per 100,000 population). Moreover, women in Poland suffer from skin cancer more often than men. In the unusual pandemic year of 2020, 124,089 new cases of malignant tumors were recorded in Poland. It was 14.7% less compared to 2019 incidence rate per 100,000 population amounted to 372.3 cases, 61.8 less than in the previous year. In 2020, fewer cases of all types of cancer were registered, but the structure of cases, considered on a national scale, was similar to 2019. In 2020, the incidence rates in the case of melanoma and others skin cancers were 36.2–10.3 cases less than in the previous year [source: <https://gus.gov.pl/rozne/tematyka/nowe-wykrycia-nowotworow-maloblastowych-w-2020-roku> (accessed on 08 June 2024)]. The COVID-19 pandemic has caused major disruptions in the delivery and use of healthcare services. Across the world, healthcare systems have seen reductions in patient visits and diagnostic tests [28, 27]. The number of MM cases diagnosed annually has decreased by ~21.37 and 23.73% in the first and second year after the pandemic, respectively, compared to pre-pandemic numbers [28]. The coronavirus pandemic has disrupted the entire healthcare system on a large scale. The pandemic had the greatest impact on screening tests due to the lockdown in April–June 2020, which resulted in a decrease in the number of

patients who were issued oncology diagnosis and treatment (DOLG) cards and were treated for cancer. Due to the pandemic, access to treatment has been significantly hampered, creating health debt that the healthcare system will now have to deal with [29–33].

It is worth emphasizing that the pandemic also had a positive impact on society by raising awareness of the importance of health and thus building awareness of the need to perform preventive tests and vaccinations [34, 35]. At the same time, due to the COVID-19 pandemic health issues have become a priority demanding more attention and influencing patient expectations, such as increased financing for access to a wider range of tests in primary healthcare.

The aim of the study was to determine the occurrence of significant risk factors for skin cancer and to assess the methods of skin cancer prevention used in the Polish population during the COVID-19 pandemic, along with the preparation of proposals for recommendations for Polish residents who are particularly predisposed to skin cancer.

2 Materials and methods

2.1 Study design, population and sampling

An anonymous survey was conducted in the form of an electronic survey. In December 2021 electronic surveys were sent to employees and students of the Medical University of Wrocław, and in January 2022 to the District Pharmaceutical Chambers and District Medical Chambers. It is difficult to determine to what extent all counties' medical and pharmaceutical chambers conducted the survey. In February 2022, electronic surveys were posted on various forums dealing with health and cancer. Subsequently, an anonymous electronic survey was conducted among patients of the Old Town Clinic in Wrocław and the Beata Kozłowska massage and rehabilitation office in Boleśławice in the period from March to December 2022. Google Questionnaire provides features for designing online questionnaires and surveys for enterprises, research institutions and private individuals. The survey consisted of 28 questions. A total of 854 participants completed the survey, including 86 (13.2%) respondents belonging to the group of people suffering from skin cancer. The study was approved by Bioethics Committee of the Medical University of Wrocław (KB10.08/2021).

2.2 Content of questionnaire

The content of the questionnaire included: [A] social characteristics, such as education (higher, secondary, doctoral, student, professional), gender (female, male), age (divided into groups 19–30, 31–40, 41–50, 51–60, 61–70, 71–80, and over 81 years); [B] type of complexion: [18] Celtic—very fair skin, light pink or white, blonde or red hair, light eye color (blue, gray or light green); does not tan, gets sunburn immediately; [28] Northern European—pale skin, red, light to dark blond and light brown hair, blue, hazel or green eye color, minimal tan, high tendency to burn; [38] Central European—light skin in warm times (beige and gold), hair from dark blonde to dark deep brown, eye color gray, hazel, green or brown, always tans, slight tendency to burn; [48]

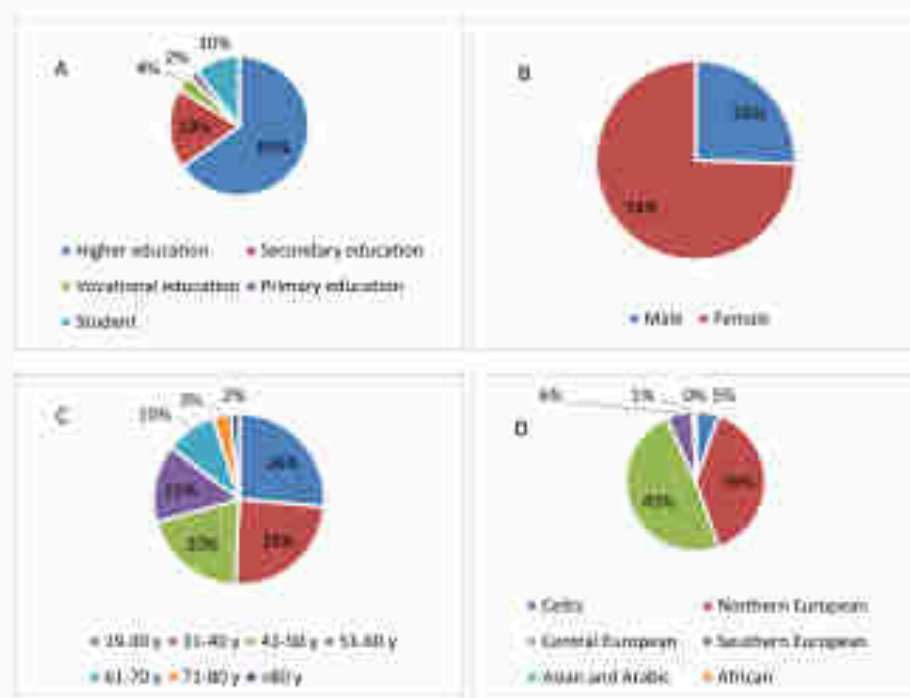


FIGURE 1

The characteristics of the study group: (A) education; (B) sex; (C) age; and (D) type of comparison.

Southern European—swarthy skin light brown or olive brown, hair dark brown or black, eyes intensely brown, always and easily tans, almost never burns; [5B] Asian and Arabic—naturally dark olive skin, black hair, dark eyes, usually brown or black, tans well, does not tend to burn; [5B] African—medium brown to dark brown skin, black hair, eye color dark brown or black, no burns—Graphic summary presented in Figure 1. [C] factors increasing the risk of skin cancer: [1C] skin disease; [2C] using sunscreen creams with sun protection factor (SPF) filter while staying in the sun; [3C] using a tanning bed; [4C] using moisturizing cosmetics after a long stay in the sun or tanning; [5C] sunburn in the past; [6C] wearing a headgear on sunny/hot days; [7C] wearing sunglasses on sunny/hot days; [8C] check-ups with a dermatologist; [9C] smoking; [10C] vitamin D supplementation; [11C] diagnosis of skin cancer in a close relative (parents, siblings, and grandparents); [12C] mole removal procedure in the past; [13C] presence of nevus: [13C.1] Sutton's, [13C.2] Becker's, [13C.3] blue; [D] knowledge about the ABCDE formula for observing moles; [E] knowledge about drugs causing photosensitization; [F] regular use of medications that may cause photosensitization; [G] diagnosed skin cancer: [1G] type of skin cancer; [2G] how many years have passed since the diagnosis of skin cancer; [3G] how many years have passed since the end of skin cancer treatment; [4G] type of treatment used.

2.3 Statistical analysis

Statistical analyses were performed with Statistica v13.0. Pearson's chi-square test was used to compare the differences between the different subgroups.

3 Results

3.1 Study sample characteristics

Figure 1 is a graphic representation of the study group. The majority of participants in this anonymous survey were respondents with higher education (65.0%), respondents with secondary education accounted for 19.0%, and 10.0% were students (Figure 1A). Due to the small number of respondents with vocational education and primary education, the inclusion criteria in the study of the impact of education were higher education, secondary education and students who were qualified for secondary education. The exclusion criteria were primary education and vocational education. The majority of respondents were women (76.0%; Figure 1B). The age of the respondents was evenly distributed (Figure 1C). The majority of respondents had the Central European skin type (22.0%) and, to a lesser extent, Northern European skin type (37.0%; Figure 1D).

The inclusion criterion for the study was the respondent's age of 19 years and over. In the case of the analysis of the impact of education on sun protection factors, the exclusion criteria were primary education and vocational education. Two educational groups were analyzed: higher education and secondary education, which also included students. From the surveyed group of respondents (811), a group of patients diagnosed with skin cancer was identified [66].

The inclusion criterion for the group of respondents suffering from skin cancer was the presence of MM—[28], BCC—[23], SCC—[7], carcinoma verrucosum (CV)—[1], benign cancer (BN)—[21], patients undergoing diagnosis of skin cancer

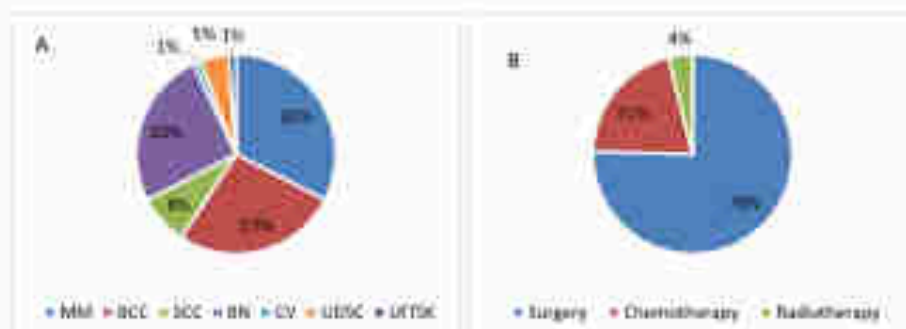


FIGURE 8

Distribution of skin cancer types (A) and treatment methods used (B) among respondents to the study group.



FIGURE 9

Respondents suffering from AD (A) ($p < 0.001$) and Ros (B) ($p < 0.001$) were diagnosed with skin cancer significantly more often.

(UDSC)–[4], patients who have lack of knowledge about the type of skin cancer, but they have been diagnosed with lack of knowledge about the type of skin cancer (LKTSK)–[1]. Three methods of skin cancer treatment, i.e., surgery [77], chemotherapy [21], and radiotherapy [4], were used in this group of skin cancer respondents. In the study group, the dominant treatment method was surgical removal of cancerous skin lesions. Figure 2 is a graphic representation of the distribution of skin cancer types among respondents (Figure 2A) and the treatment methods used (Figure 2B).

3.2 Factors increasing the risk of skin cancer

3.2.1 Skin diseases

The chronic inflammation, which occurs in inflammatory skin disease, can damage DNA and potentially alter the risk of mutations that lead to cancer [83], the co-occurrence of other skin diseases may increase or decrease the risk of skin cancer. Recent data suggest a decreased risk of MM in people with atopic dermatitis (AD), but an increased risk of other skin cancers, especially non-melanoma skin cancer (NMSC), including BCC and SCC [30, 87]. The study respondents suffering from AD were also diagnosed with skin cancer more often ($p < 0.001$, 29.5 vs. 11.0%, Figure 3A). AD is a chronic recurrent inflammatory skin disease associated with epithelial, immune, and environmental

factors, which is characterized by activation of the type 2-mediated immune response in the skin breakdown of the skin barrier, and intense itching [88].

Rosacea (Ros) is the most common inflammatory skin condition among adult inhabitants of Northern European with light-skinned heritage [89], which is characterized by facial erythema, pustule papules, and telangiectasia. UVB from natural sunlight can worsen Ros symptoms [90]. Ros and cancer are believed to be linked by the common occurrence of inflammatory disorders and immune response disorders [32]. Participants with Ros were significantly more likely to suffer from skin cancer ($p = 0.002$, 32.3 vs. 12.4%, Figure 3B).

Alopecia areata (AA) is a chronic, inflammatory, common autoimmune disease characterized by non-scarring hair loss that affects all ages, both sexes, and all skin types [41]. However, current data show that individuals of non-Caucasian origin are more prone to disease development [42]. Psychological stress has been proposed as an external factor that contributes to the development of AA [43]. However, histological examination revealed inflammatory cell infiltrates around the bulbar region of hair follicles in patients with AA [44]. The conducted research presented that, similarly to survey participants suffering from AD and Ros, respondents diagnosed with AA are more likely to suffer from skin cancer ($p < 0.001$, 86.7 vs. 11.5%, Figure 3A).

Acne vulgaris (AV) is common among young people [45] and reflects hormonal imbalance and may be a key component of many systemic diseases. It was hypothesized that the diagnosis of AV



FIGURE 4

The respondents suffering from MM were more likely to have been diagnosed with skin cancer (B) ($p = 0.001$), whereas those suffering from AV were more likely not to have skin cancer (A) ($p = 0.029$).

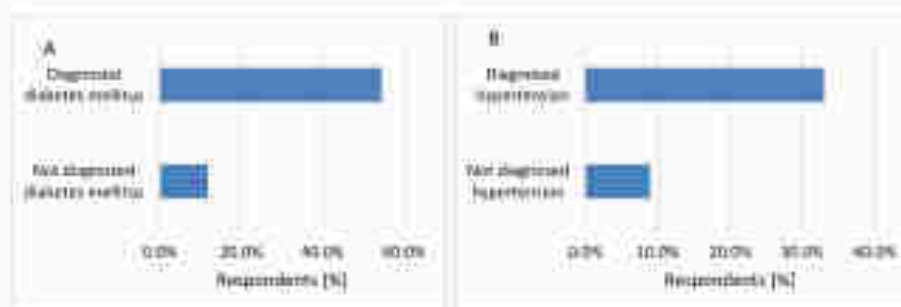


FIGURE 5

Respondents suffering from DM (A) ($p < 0.0001$) and hypertension (B) ($p = 0.005$) were diagnosed with skin cancer significantly more often.

in adolescents may predict subsequent cancer risk (46). However, respondents in this study with AV were significantly more likely not to suffer from diagnosed skin cancer ($p = 0.029$, 5.8 vs. 14.3%, Figure 4b).

3.2.2 Other chronic diseases

Diabetes mellitus (DM) is defined as a chronic, systemic condition characterized by hyperglycemia, leading to severe complications, including neuropathy. There is a significant portion of diabetic patients experiencing skin-related complications. The issues arising from DM are largely attributed to chronic hyperglycemia and elevated fatty acid levels, with oxidative stress playing a crucial role in the patho-mechanism of this disease (47). The state of oxidative stress in diabetes, with consequential DNA damage, is also considered responsible for the transformation of oncogenes and development of cancers (48). This study showed that respondents diagnosed with diabetes have an increased risk of skin cancer ($p < 0.001$, 54.5 vs. 11.8%, Figure 5a).

Hypertension is defined as high systolic and/or diastolic blood pressure (49). Several anti-hypertensive drugs are photosensitizing and may therefore act as co-carcinogens with UVR, which can increase the risk of skin cancer (50, 51). Some studies indicated that the use of hydrochlorothiazide was associated with an increased risk of SCC but no association was observed for BCC or melanoma

(31). This study showed that the presence of hypertension increases the risk of skin cancer ($p < 0.001$, 33.0 vs. 9.0%, Figure 5b).

Rheumatoid arthritis (RA) is a chronic inflammatory condition with joint swelling, pain and stiffness (33). This study indicated that suffering from RA increases the risk of skin cancer ($p < 0.001$, 44.4 vs. 12.5%, Figure 6a). A Swedish study showed the risk of NMBC may be increased in patients with RA (34). An increased risk of MM in inflammatory bowel disease, including Crohn disease (CD) has been reported (53, 54). Also, the greatest risk of NMBC was indicated for CD patients (57). Treatment with thiopurine for more than 5 years was associated with a significantly increased risk of NMBC (55). Respondents diagnosed with CD are more likely to suffer from skin cancer ($p < 0.001$, 71.4 vs. 12.6%, Figure 6b).

3.2.3 Dependence of skin complexion type and age on the occurrence of cancer

Skin cancer is more common in older people. Mostly NMBC appears after 50 years of age. In recent years, skin cancer dramatically increased in people older than 65 years of age. Skin cancer also develops in younger people, when they have fair skin (59). Moreover, older age, male gender, Caucasian ethnicity are associated with a substantially increased risk of MM (60). Statistically, skin cancer was diagnosed more often in participants with Celtic complexion compared to respondents with Central European complexion ($p < 0.001$, 42.9 vs. 9.2%) and Northern

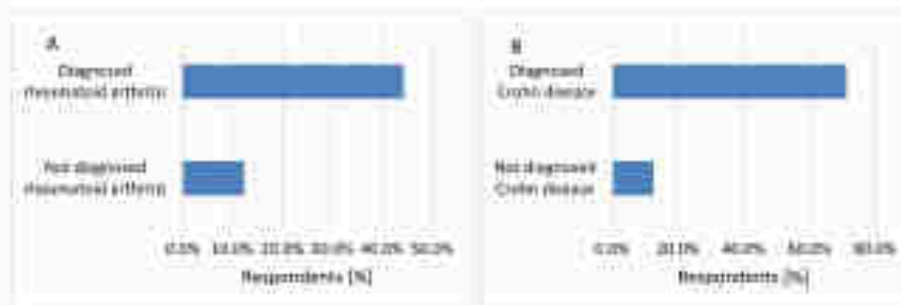


FIGURE 6

Respondents suffering from RA (B) ($p = 0.002$) and CD (B) ($p = 0.022$) were diagnosed with rheumatism or significantly more often.

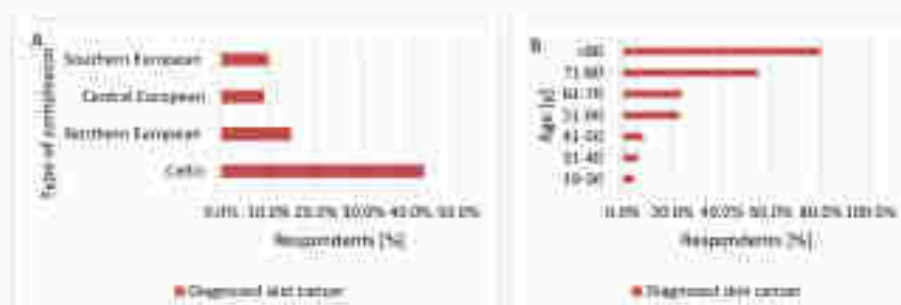


FIGURE 7

Skin cancer was diagnosed more often in respondents with Celtic complexion compared to respondents with Central European complexion ($p < 0.002$) and Southern European complexion (B) ($p = 0.002$). The incidence of skin cancer increased with age of participants (B) ($p < 0.002$).

European complexion ($p < 0.001$, 42.6 vs. 14.8%; [Figure 7A](#)). The incidence of skin cancer increased with age ($p < 0.001$, 54.6 vs. 4.7%–23.0% for 71–80 years and 80.0 vs. 4.7%–23.0% for >80 years; [Figure 7B](#)).

3.2.4 Using sunscreen creams with SPF filter while staying in the sun and the using moisturizing cosmetics after a long stay in the sun or tanning

UVR is a major risk factor for developing MM, so re-protecting your skin from UVR exposure is crucial to maintaining protection against sunburn and an increased risk of future skin cancer. Sunscreens reduce the intensity of UVR acting on the epidermis, thus protecting against sunburn. Most sunscreens are chemicals that absorb various UVR wavelengths, mainly in the UVR range (1). The use of sunscreen reduces both the development of premalignant actinic keratosis and the recurrence of SCC, and at the same time, the use of sunscreen early in life may play an important role in the prevention of BCC (61).

Men are more likely not to use SPF sunscreen compared to women ($p < 0.001$, 31.1 vs. 14.5%). If men use creams with SPF, they are more likely to choose creams with SPF20 ($p < 0.001$, 22.2 vs. 12.2%). Women are statistically more likely to choose sunscreen with SPF50 ($p < 0.001$, 43.8 vs. 25.2%) and SPF30 ($p < 0.001$, 25.2 vs. 17.4%; [Figure 8A](#)). Younger age groups, especially the group of respondents 19–30 years old, use creams with SPF50 filter statistically more often compared to other groups

($p < 0.001$, 51.7 vs. 27.0%–39.2%). The 31–40 years age group of respondents uses SPF50 creams statistically significantly more often compared to other groups of respondents ($p < 0.001$, 55.5 vs. 19.9%–22.3%). In the group of older respondents over 70 years of age, they are more likely not to use SPF creams compared to younger respondents ($p < 0.001$, 40.9 vs. 12.0%–31.0% for 71–80 years) and ($p < 0.001$, 60.8 vs. 12.3%–31.0% for <30 years; [Figure 8B](#)).

Respondents with Celtic skin type ($p < 0.001$, 31.4 vs. 36.4%) and Northern European skin type ($p < 0.001$, 43.8 vs. 36.4%; [Figure 9](#)) choose sunscreens with SPF50 compared to people with Central European skin type. Respondents with Southern European skin type ($p < 0.001$, 27.5 vs. 14.8%), Central European skin type ($p < 0.001$, 20.3 vs. 14.8%), Celtic skin type ($p < 0.001$, 22.8 vs. 14.8%) do not use sunscreen creams statistically more often than respondents with Northern European skin type. The rare use of sunscreens with SPF40 may be due to their lower availability, but also to the fact that dermatologists recommend using sunscreens with SPF50.

Moisturizing prevents and alleviates skin irritation, soothing the skin by slowing the evaporation of water. Moisturizing creams are appropriate for patients with dry, sun-damaged skin (62). Women were more likely to apply moisturizing creams after longer exposure to the sun ($p < 0.001$, 85.7 vs. 46.1%) compared to men ([Figure 10A](#)). Older age groups of respondents over 70 years of age were more likely not to apply moisturizing creams after prolonged sun exposure compared to younger groups of respondents (p

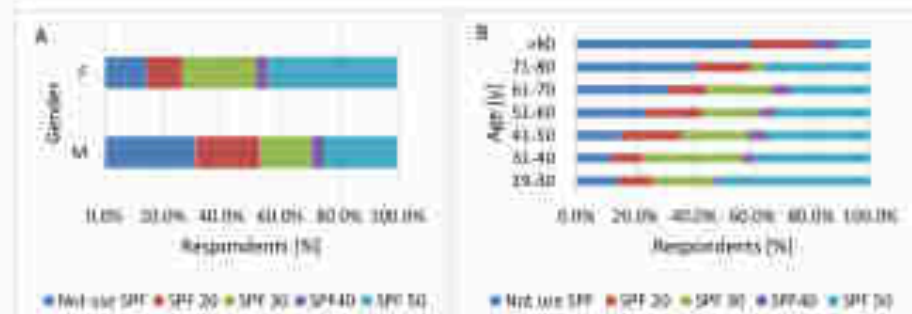


Figure 10

Gender (A) and age (B) differences in SPF sunscreen use: men are more likely not to use SPF sunscreen compared to women ($p < 0.001$). Women are statistically more likely to choose sunscreen with SPF50 ($p < 0.001$) and SPF30 (A) ($p < 0.001$). Younger age groups, especially those aged 20–30 years, use SPF50 sunscreen significantly more often than other groups (B) ($p < 0.001$).

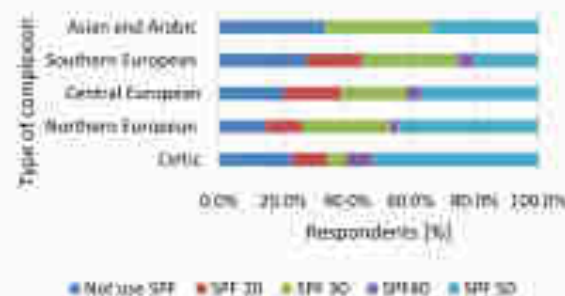


Figure 11

Respondents with Celtic skin type ($p < 0.001$) and Northern European skin type ($p < 0.001$) choose sunscreens with SPF50.

< 0.001 , 68.2 vs. 18.0%–23.8% for 71–80 years and 60.0 vs. 18.0%–23.8% for <30 years, [Figure 10B](#)).

3.2.5 Using a solarium

Tanning beds emit primarily UVA radiation, although a small amount (5%) is in the UVB range. The intensity of UVA radiation produced by large tanning units can be 10–15 times higher than that from the midday sun [1]. Using a solarium is associated with a significantly increased incidence of MM diagnosed before the age of 50–60 years by over 70% [61, 62]. People with fair skin are most at risk for skin cancer [63]. Only 25 respondents use solariums, but it was shown that women use solariums significantly more often than men ($p = 0.039$, 4.8 vs. 1.2%, [Figure 11](#)). Of these 25 respondents, six developed skin cancer – MM [3], benign skin cancer [2] and the type of diagnosed skin cancer was unknown [1].

3.2.6 Sunburn in the past

Previous sunburn may increase the likelihood of developing MM, especially at a young age [17, 64]. Melanocytic nevi exposed to sunburn levels of UVR show increased melanocytic localization and cellular infiltration resembling primary MM [65]. UVA rays

pass deeper into the skin and can induce deeper skin damage, such as elastosis. UVB rays predominantly cause erythema or sunburn [66]. A total 515 respondents had a history of sunburn. The majority of respondents (79.1%) in this study had a history of sunburn. Respondents with Southern European skin were least likely to declare having suffered sunburn compared to respondents with Northern European skin ($p < 0.001$, 47.5 vs. 88.7%), Central European ($p < 0.001$, 47.5 vs. 76.3%), and Celtic skin ($p < 0.001$, 47.5 vs. 74.2%, [Figure 12](#)).

3.2.7 Wear headgear and sunglasses on sunny/hot days

MM develops in parts of the body exposed to sunlight, and the frequency of melanoma lesions increases with age and the duration of exposure to UVR [37], so it is very important to ensure adequate protection of the body during exposure to UVR. Men wear headgear significantly more often than women on sunny/hot days ($p < 0.001$, 74.9 vs. 40.1%, [Figure 13A](#)). The older the respondents, the more often they wear headgear on sunny/hot days when comparing age groups over 70 years with younger groups ($p = 0.040$, 81.8 vs. 55.2%–73.0% for 71–80 years and 80.0 vs. 55.2%–73.0% for <30 years, [Figure 13B](#)).

Respondents with higher education wear sunglasses more often compared to respondents with secondary education ($p = 0.018$, 80.4 vs. 71.8%). Women wear sunglasses significantly more often than men ($p = 0.018$, 76.5 vs. 68.3%, [Figure 14A](#)). Older participants are more likely not to wear sunglasses on sunny/hot days ($p < 0.001$, 34.8 vs. 17.7%–27.3% for 71–80 years and 80.0 vs. 17.7%–27.3% for <30 years, [Figure 14B](#)).

3.2.8 Smoking

Tobacco smoking is a risk factor for several cancers. In a hospital-based case-control study, a relationship was demonstrated between smoking and being diagnosed and the occurrence of SCC [68]. A meta-analysis of 15 studies, published between 1990 and 2018, found that current smoking was associated with higher risk of SCC but with lower risk of BCC and MM [69]. The results of a cohort study suggest that patients with clinical stage

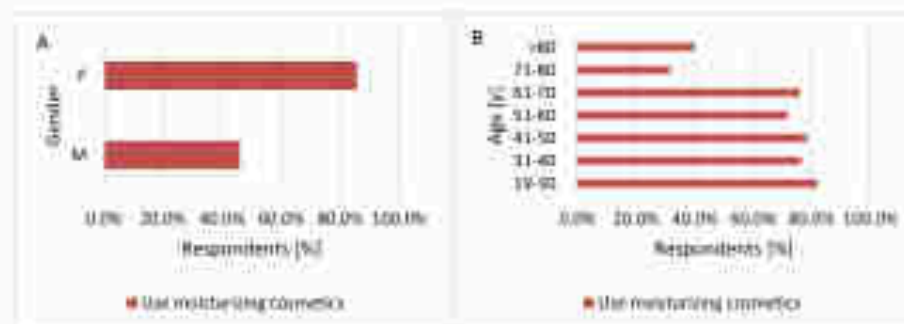


FIGURE 14

Gender (A) and age (B) differences in the use of moisturizing cosmetics after photoprotection: women were more likely to apply moisturizing cosmetics after photoprotective exposure (A) ($p = 0.001$). Older respondents (71+ years) were more likely to use moisturizing cosmetics after extended sun exposure (B) ($p = 0.001$).

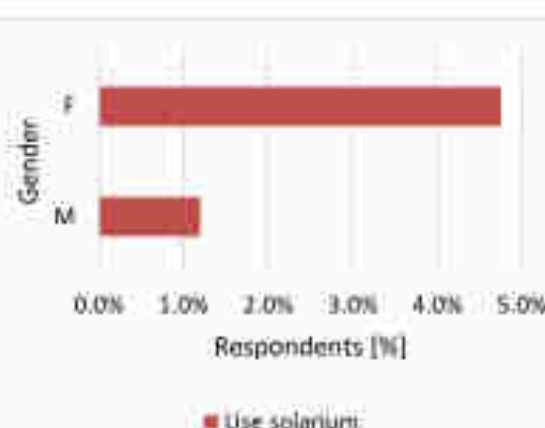


FIGURE 15

Women use solarium significantly more often ($p = 0.008$).

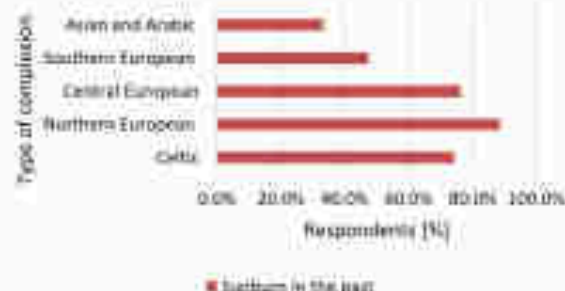


FIGURE 16

Solarium was least common among respondents with Southern European skin ($p = 0.001$) and most common among respondents with Northern European type of complexion.

I and II MM) who smoked cigarettes had a significantly increased risk of death from MM (70). Most study participants do not smoke cigarettes—562 respondents. However, the study showed

that men smoke tobacco more often than women ($p = 0.008$, 21.6 vs. 11.0%, Figure 15A). The majority of respondents who smoke tobacco are over 70 years of age ($p = 0.004$, 21.8 vs. 9.5%–14.6% for 71–80 years and 40.0 vs. 9.5%–14.6% for <40 years, Figure 17B).

3.2.9 Vitamin D supplementation

The main source of vitamin D for most people is sensible-sun exposure (71, 72). The vitamin D receptor has been identified in both normal melanocytes and melanoma cells (73). Several epidemiologic studies suggest that exposure to sunlight, which enhances the production of vitamin D₃ in the skin, is important in preventing many chronic diseases (74). Both low and high levels of vitamin D are associated with an increased risk of MM (3, 23, 75). It has also been shown in an Italian case-control study that adequate dietary vitamin D reduces the risk of MM (76, 77). Vitamin D has protective effects against breast, colon, prostate cancer and even NMSC (78). Most study participants supplement vitamin D—475 respondents. Women supplement vitamin D more often than men ($p < 0.001$, 76.7 vs. 62.3%, Figure 16).

3.2.10 Diagnosis of skin cancer in a close relative (parents, siblings, and grandparents)

The risk of MM increases 30–70 times in people with a significant family history of melanoma (79). There are genes whose mutations can lead to hereditary MM, such as CDKN2A and TP53 encoding protein 53 (p53) (17). Approximately 8%–10% of patients with MM have a first-degree relative with the disease. Other possible explanations for family incidence could be that the family tends to spend more time in the sun, family members share a similar skin type, or both (80). Respondents with Celtic complexion were much more likely to have people diagnosed with skin cancer in their family compared to other Central European ($p = 0.014$, 28.6 vs. 10.4%), Northern European ($p = 0.014$, 28.6 vs. 13.7%), and Southern European complexions ($p = 0.014$, 28.6 vs. 2.5%, Figure 17). Respondents with Southern European complexion very rarely had a person in their close family with skin cancer compared to people with Central European complexion ($p = 0.014$, 97.5 vs.

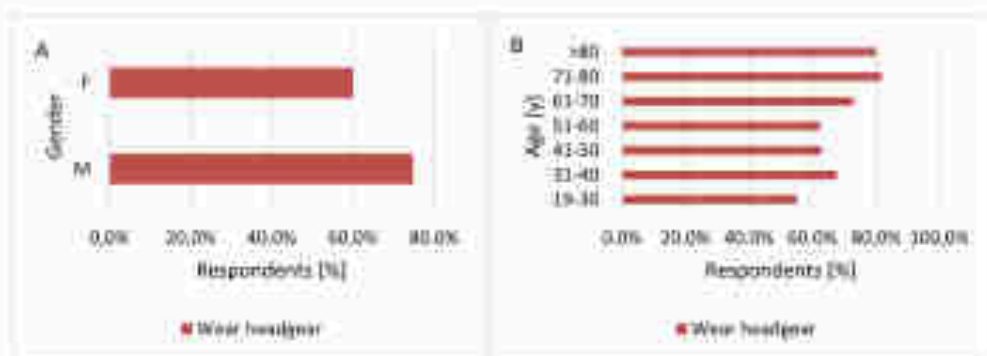


FIGURE 13

Gender (A) and age (B) differences in headgear use on sunbathing days: men wear headgear significantly more often than women (A) ($p = 0.022$). Additionally, older respondents showed a statistically significant tendency to wear headgear more frequently (B) ($p = 0.042$).

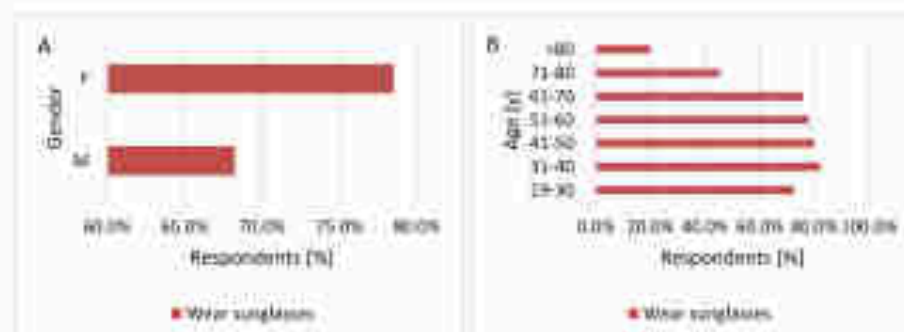


FIGURE 14

Gender (A) and age (B) differences in wearing sunglasses on sunny/ hot days: women are more likely to wear sunglasses than men (A) ($p = 0.028$). However, older respondents are statistically significantly less likely to wear sunglasses (B) ($p = 0.001$).

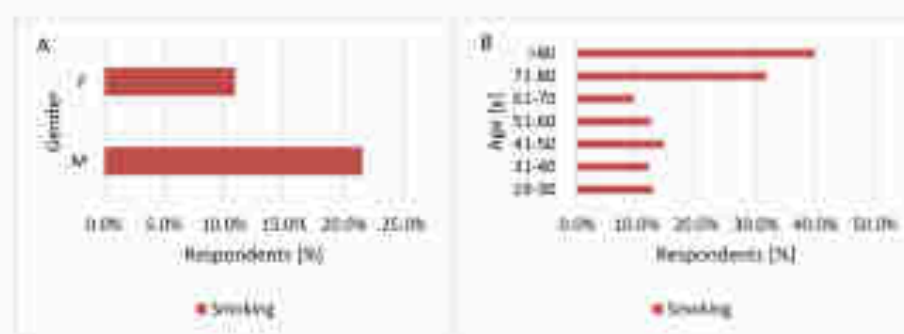


FIGURE 15

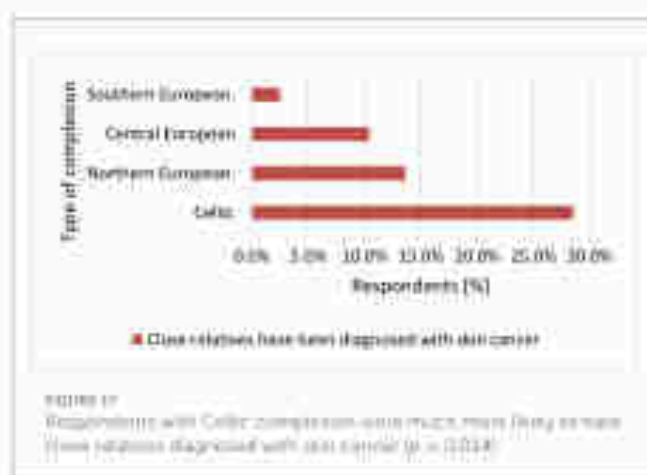
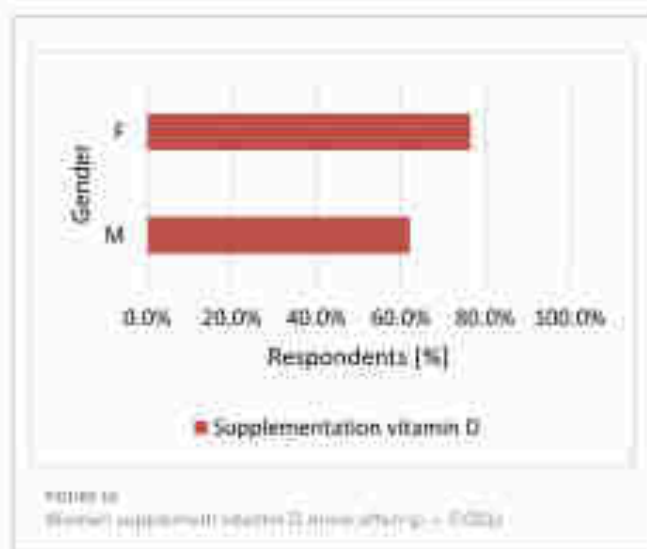
Gender (A) and age (B) differences in tobacco smoking: most respondents did not smoke tobacco, but men were significantly more likely to be smokers (A) ($p = 0.002$). Additionally, the majority of tobacco smokers were over 70 years of age (B) ($p = 0.034$).

88.8%), Northern European ($p = 0.014$, 97.5 vs. 88.3%), and Celtic ($p = 0.014$, 97.5 vs. 71.4%).

3.2.11 Mole removal procedure in the past and presence of nevi (1) Sutton's (2) Becker's (3) blue

The presence of multiple common or unusual moles is an accepted factor indicating an increased risk of developing MM.

Benign melanocytic lesions may also act as precursors to MM (10, 11). The formation of moles is modulated by various factors, including pigmentation, genetic factors and sun exposure (7). Although pigment phenotypes and hallmarks of MM risk factors have been established, the magnitude of these associations may vary depending on geographic region. Australians have on average around three times as many moles as those living in the UK, which contributes to the higher incidence of MM in Australia (82). A



total of 254 respondents had a mole removed. The study indicated that moles are removed more often with age, especially over 70 years of age compared to other age groups ($p < 0.001$, 66.2 vs. 24.2%–49.0% for 71–80 years and 70.0 vs. 24.2%–49.0% for >80 years) (Figure 18A).

Melanocytic nevi are frequently accompanied by inflammatory cells of different types, in varied amounts and distributed in different patterns. Sutton's nevus is a peculiar type of regressing melanocytic nevus, also known as halo nevus (63). Sutton's nevi are found in ~1% of young adults. The most common sites for Sutton's nevi are the back, followed by head and neck (64). Clinically, the nevus is surrounded by a peripheral hypopigmented halo. The amount of the inflammatory infiltrate in halo nevus varies from moderate to dense (65). There are many diseases that have been described in individuals with Sutton's nevi, such as vitiligo, thyroid diseases, and neoplasia (66). Sutton's nevus appears significantly more often as the respondent's age increases. When comparing the 19–30 years age group with other age groups, Sutton's nevi occur significantly more often in older respondents ($p = 0.007$, 2.8 vs. 1.9%–20.0%, Figure 18B).

Becker's nevus is a cutaneous hamartoma characterized by circumscribed hyperpigmentation with hypertrichosis. There have

been reported in the literature of some patients with acneiform lesions of Becker's nevus and the hypothesis is that this lesion may be mediated by androgens (67). Becker's nevi do not pursue a malignant course but may become cosmetically problematic (68). In this study Becker's nevus occurs more often in men than in women ($p = 0.038$, 13.8 vs. 8.7%, Figure 19A). This is also confirmed by literature data, which describe the occurrence of Becker's nevi 4–6 times more often in men than in women (67). In the study population, Becker's nevus appears more often after the age of 70 ($p = 0.029$, 13.4 vs. 6.9%–12.5% for 71–80 years and 40.0 vs. 6.9%–12.5% for >80 years, Figure 19B). Most respondents did not observe the above-mentioned moles—Sutton's nevus (21), Becker's nevus (63), blue birthmark (40). In the group of people who suffered from skin cancer—Sutton's nevus (10), Becker's nevus (17), and blue birthmark (7).

3.2.12 Knowledge about the ABCDE formula for observing moles and check-ups with a dermatologist

Currently, early detection strategies for MM include teaching how to recognize suspicious lesions. The ABCDE rule describes established criteria for the occurrence of a malignant tumor by asymmetry (A), irregular borders (B), color variation (C) and diameter generally >6 mm (D), evolution (E)—in size, shape, color, surface (69, 70). More women know the ABCDE formula compared to men ($p < 0.001$, 49.2 vs. 31.7%, Figure 20A). Younger respondents know the ABCDE formula more often than older ones ($p < 0.001$) when comparing the 19–30 years age group with other groups ($p < 0.001$, 61.6 vs. 20.0%–46.9%, Figure 20B). What is more, only 258 respondents (38.4%) make follow-up visits to a dermatologist.

3.2.13 Knowledge about drugs causing photodermatoses and occurrence of photodermatoses after taking medications

Photodermatoses are cutaneous photosensitivity reactions that are an adverse reaction to drugs caused by exposure to sunlight (90, 91). UVR can induce an inflammatory reaction (phototoxicity) or a T-cell-mediated reaction (photoallergy). Photosensitive drugs are activated on sun exposure and undergo chemical reactions. Most photosensitive reactions are caused by UVA rather than UVB radiation (90). Not only are photosensitive reactions a cause of significant morbidity, but in some instances, pose a future risk for malignancy, specifically keratinocyte carcinoma and MM (77, 92).

Women were more likely to know that using medications could cause the occurrence of photodermatoses compared to men ($p < 0.001$, 68.4 vs. 32.3%, Figure 21A). Respondents up to 70 years of age more often knew that drugs cause photodermatoses, especially respondents belonging to the youngest age group. Most people knew that drugs could cause photodermatoses in the 19–30 years age group compared to the other groups ($p < 0.001$, 78.2 vs. 33.8%–68.3%, Figure 21B).

Most often, photodermatoses in the group of surveyed respondents occurred after medications used for hypertension and angina, as well as contraceptives in women. Respondents using

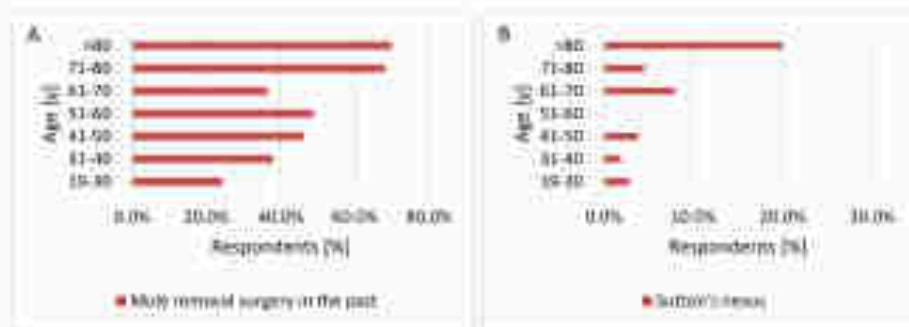


Figure 16 Age-related differences in mole removal (A) and Sutton's nevus occurrence (B). Mole was removed more frequently with age (A, $p = 0.001$). Sutton's nevus is significantly more common in older respondents (B, $p = 0.004$).



Figure 17 Gender (A) and age (B) differences in Becker's nevus occurrence. Becker's nevus occurs more often in men (A) ($p = 0.001$) and in respondents over the age of 70 (B) ($p = 0.002$).

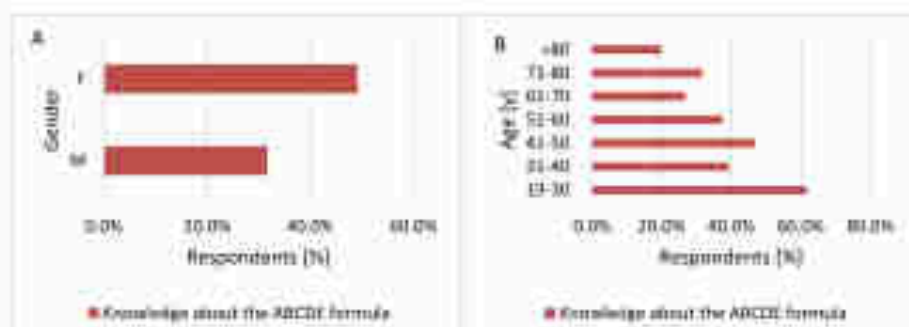


Figure 18 Gender (A) and age (B) differences in knowledge of the ABCDE formula. More women (A) ($p = 0.001$) and younger respondents (B) ($p < 0.002$) are familiar with the ABCDE formula.

medications that may cause photodermatoses suffered from skin cancer more often ($p < 0.001$, 21.6% vs. 7.7%) (Figure 22).

Participants using medications causing photodermatoses more often experienced sunburn statistically significantly ($p = 0.003$, 64.6 vs. 25.3%, Figure 23) and had their moles removed ($p = 0.014$, 44.8 vs. 35.2%, Figure 24).

Participants using medications causing photodermatoses were significantly more likely to have Sutton's nevus ($p = 0.004$, 5.0 vs.

2.0%, Figure 23A) and Becker's nevus ($p < 0.001$, 15.1 vs. 8.1%, Figure 23B).

4 Discussion

The etiology of skin cancer is multifactorial, involving a complex interplay of genetic, environmental, and behavioral factors

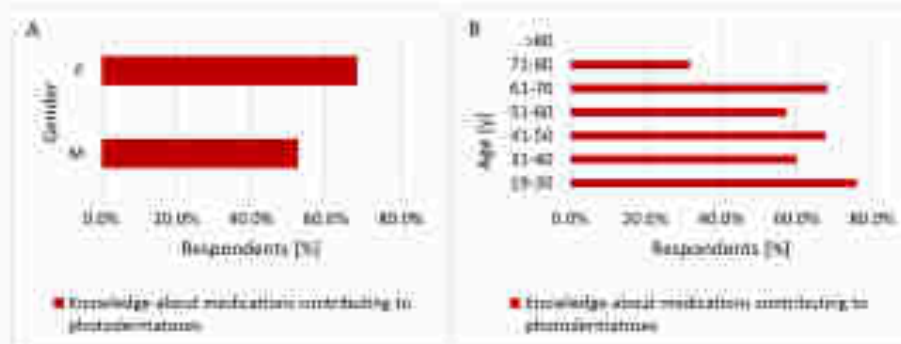


FIGURE 19

Gender (A) and age (B) differences in awareness of medications causing photodermatosis were higher (A) ($p < 0.001$) and higher (B) ($p < 0.001$) in those that using medication compared to the occurrence of photodermatosis.

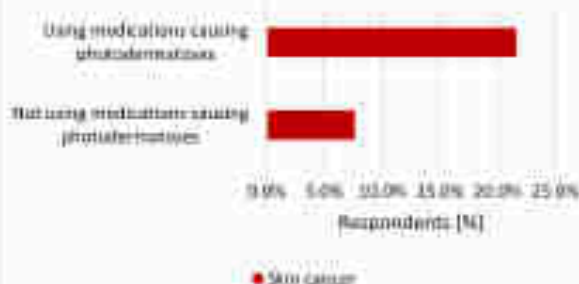


FIGURE 20

Respondents using medications that may cause photodermatosis suffered from skin cancer or were others ($p < 0.001$).



FIGURE 21

Respondents using medications causing photodermatosis more often ($p < 0.001$) had their melanoma surgery ($p < 0.001$).

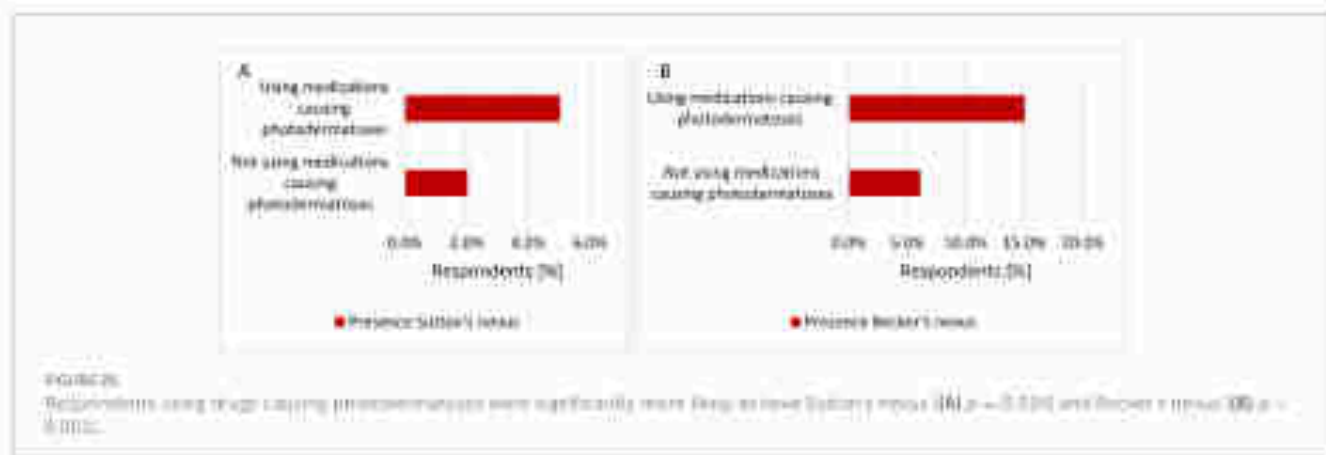


FIGURE 22

Respondents using medications causing photodermatosis more often experienced sunburn ($p < 0.001$).

4.3.3. The occurrence of selected skin diseases may predispose to skin cancer. Increasing evidence suggests that the increased risk of malignant tumors is associated with the occurrence of chronic inflammation, including AD (44). In this study, participants with AD were statistically significantly more likely to suffer from skin

cancer ($p < 0.001$). There are conflicting data regarding the risk of skin cancer in patients with AD. A meta-analysis based on published searches in MEDLINE and Embase from 1946 and 1980, respectively, to January 3, 2019, including eight cohorts of population-based studies and 48 case-control studies, showed a statistically significant association between AD and keratinocyte carcinoma. No evidence was found of an association between AD and other cancers, including MM (45). A review of PubMed and Embase databases conducted through August 4, 2021, by another research group showed that AD is statistically significantly associated with an increased risk of BCC and SCC, but not MM (46). Similar results were obtained in a large cohort study conducted in Denmark in 1977–2006, where an inverse relationship between the co-occurrence of AD and MM was confirmed. At the same time, an increased risk of BCC and SCC has been demonstrated among people with AD (47). Also, an Indian research group found that the risk of developing BCC is increased in patients with AD, while the risk of developing MM is not increased (48). Of note, an increased risk of overall cancer was found in patients with AD compared with patients without AD (49, 50). In a case-control study conducted at United Kingdom, it was not found that patients with AD had a higher risk of developing skin cancer other than MM than other patients with dermatological diseases (51).



Atopic allergic conditions, such as AD, may indicate a heightened immune response, which could contribute to recognizing and removing malignant cells and thus reducing cancer risk. On the other hand, AD is accompanied by repeated tissue inflammation, damage, and repair, which could increase the risk of cancer [85, 88, 89]. Mediators of the Th1 pathway also may divert tissue immunity away from an anti-tumor Th1 response (i.e., IgG1, TNF- α) and toward an IgE response against allergens, and not tumor antigens through "inappropriate Th1 immune skewing" [100]. Moreover, chronic stimulation of the immune system by an antigen will induce the development of random pro-oncogenic mutations and therefore result in an increase in cancer risk. That is why, the possibility of a promoting or protective role of AD in carcinogenesis has been an interesting research area over the years [86, 98, 99]. Furthermore, immunosuppressive therapies for AD such as local steroids, calcineurin inhibitors and various systemically administered treatments (i.e., azathioprine and cyclosporine) as well as UV treatment may possibly increase the risk of cancer in general including MM [87, 101, 102].

Also, in this study participants with Ros were significantly more likely to suffer from skin cancer ($p = 0.002$). In a Denmark study an increased risk of NMSC was found among patients with Ros [43]. Additionally, a cohort study in a Korean population with Ros showed an increased risk of actinic keratosis and keratinocyte carcinomas [103]. In turn, the Nurses' Health Study II in the US found that the occurrence of Ros is associated with an increased risk of developing BCC [104, 105]. Moreover, a German study indicated that Ros is strongly associated with MM in Caucasians [106]. Several human and animal studies have shown that the most common cause of MM is cumulative exposure to UVA and UVB radiation. Exposure to UVA radiation leads to oxidative stress-induced DNA damage, and UVB induces the formation of photoproducts and the accumulation of DNA mutations. The activation of inflammatory cells such as macrophages and neutrophils during skin inflammation is associated with a malignant change in melanocytes. Due to the role of chronic inflammation and the immune system in the pathophysiology of Ros, it seems justifiable to assume that patients diagnosed with Ros have an increased predisposition to developing MM [68, 108–110].

While the exact etiology of AA is unclear, the pathogenesis of AA is known to involve immune-mediated and inflammatory

processes [111]. This study showed that respondents diagnosed with AA are more likely to suffer from skin cancer ($p = 0.001$). A study from the US showed a reduced risk of developing NMSC and a trend toward a reduced risk of MM in patients with AA [112]. Recent studies have demonstrated a decreased risk of MM and NMSC in vitiligo patients [113]. AA has also been associated with a three- to eight-fold higher incidence of vitiligo, a skin disorder characterized by autoimmune destruction of melanocytes [114]. AA and vitiligo share a similar pathogenesis, in which CD8⁺ T cells and IFN- α play an active role [115]. A retrospective cohort study conducted also in the US presented a decreased risk of NMSC and a trend toward decreased risk MM in patients with AA [112]. A Taiwanese study showed that the risk of NMSC was significantly lower in patients with AA [115]. Also, in a study of the Korean population, the incidence of skin cancer did not increase in patients with AA [116]. It's worth adding that few theories describe the potentially significant contribution of reactive oxygen species (ROS) in the pathogenesis of AA, as in AD. The results suggest that decreased antioxidant enzyme activity likely contributes to increased oxidative stress observed in patients with AA, which may indicate a common pathogenesis of AD and AA [117].

A new risk factor for the development of MM may be the occurrence of adolescent AV. A 20-year study of nurses (Nurses' Health Study II) in the US population found that women with a history of severe acne had an increased relative risk of MM. What is more, adolescents with acne were more likely to have birthmarks [40]. In our study different results were obtained. Participants diagnosed with AV were significantly more likely not to suffer from skin cancer ($p = 0.029$, 5.3 vs. 14.3%). The obtained result indicating the protective effect of AV against skin diseases may be due to the fact that the respondents who took part in this survey and suffered from AV were mainly from younger age groups. The risk of skin cancer increases with age, and in this case, it is difficult to assess the impact of AV on older groups of patients suffering from skin cancer.

Current evidence also suggests that patients with psoriasis may have a higher risk of developing NMSC than patients without psoriasis [118, 119]. In a Danish population study, a moderately increased risk of developing MM and NMSC was observed in patients with mild psoriasis, while in patients with severe psoriasis and psoriatic arthritis, the risk of developing NMSC was increased

but did not extend to the risk of MM. Psoriasis is commonly treated with UV phototherapy and immunosuppressive drugs, which may increase the risk of skin cancer [320, 321]. This study did not confirm the contribution of psoriasis to the pathogenesis of skin cancer.

DM is associated with increased prevalence of cancer including both MM and SCC [122]. However, there is a lack of epidemiological data linking DM to photo-carcinogenesis [67]. Genetically primed elevated levels of HbA1c were found to be suggestively associated with a reduced risk of MM [123]. Our study found that respondents diagnosed with DM have an increased risk of skin cancer ($p < 0.001$). Among men with DM, the risk of skin cancer has increased significantly in the Chinese population [244]. In the Taiwanese population the incidence rate and risk of developing overall skin cancer, including NMSC, was significantly higher in older adults with DM [121]. Recently, studies have also implicated vitamin D deficiency, as well as vitamin D receptor gene (VDR, Rarr, Tag1) polymorphism in the increased risk of developing both DM and MM [66].

Studies have suggested that certain glucose-lowering medications, including metformin, thiazolidinediones, insulin, and incretin-based therapies, are associated with decreased or increased risk of cancer [326]. Patients using exogenous insulin had a lower risk of developing NMSC, and the protective effect of insulin use becomes more distinct with increasing age [327]. Also, metformin use is associated with a decreased skin cancer risk [328]. A new concept in dermat-oncology is that treatment of DM and prevention of skin cancer are two sides of the same coin [122]. In a Canadian population-based cohort study, glucagon-like peptide-1 receptor agonists (GLP-1 Ras) were not associated with an increased risk of NMSC or MM, compared with sulfonylureas [329]. What is more, dipeptidyl peptidase 4 (DPP-4) inhibitors were associated with a reduced risk of MM but not NMSC, compared with sulfonylureas [330].

The association between hypertension and MM is unclear. This study found that hypertension increases the risk of skin cancer ($p < 0.001$). Used in therapy of hypertension hydrochlorothiazide is associated with a substantially increased risk of NMSC, especially SCC [111]. In meta-analysis users of calcium channel blockers (CCB) were at increased skin cancer risk while β -blockers users were at increased risk of developing MM. There was no association between thiazide diuretics, angiotensin converting enzyme inhibitors (ACEi), angiotensin receptor blockers (ARB) use and skin cancer risk [331]. A meta-analysis by a Netherlands group found that exposure to diuretics and CCB was associated with an increased risk of NMSC. This may be explained by their photosensitizing properties. Drug-induced photosensitivity indicates an adverse reaction of the skin due to the combination of sun exposure and a pharmacological compound. Medications in the skin may be affected by UVR, leading to the formation of ROS. This can not only lead to photo-genotoxicity but also activate immune cells and the release of cytokines [137]. Another meta-analysis indicated that thiazide diuretics are associated with the risk of all skin cancer types, including MM [138]. Recent studies have shown a cumulative dose-dependent association between the use of hydrochlorothiazide and skin cancer, including MM and NMSC, in Western Europe [135, 136].

Skin cancers were increased among treated patients with RA [337]. Our study found that suffering from RA ($p < 0.001$) and CD ($p = 0.001$) increases the risk of skin cancer. The use of TNF inhibitors [338, 339] and prednisone in patients with RA was associated with an increased risk of NMSC [140]. Anti-TNFs have been reported to increase the risk of MM, particularly in CD [141]. Several large patient registries and clinical trial data have demonstrated the potentially causal role of immunomodulatory therapy (methotrexate, azathioprine) in the development of skin cancer; these are also administered in CD and psoriasis [342, 343]. Methotrexate-treated RA patients have an increased incidence of MM [144], and biologic therapy in RA and CD is associated with increased risk for NMSC and MM [345, 346–348].

Our study showed that, in addition to the increased risk of skin cancer in the Polish population with the coexistence of one of the diseases such as AD, RA, AA, DM, hypertension, RA, and CD, respondents using drugs that may cause photodermatoses suffered from skin cancer more often. This confirms that, in addition to chronic inflammation in skin diseases, an important role in the development of skin cancer is played by chronic photosensitive drugs, which are prescribed for AD, RA, AA, hypertension, RA, CD, and DM. Another result confirming that the photosensitizing drugs used may be responsible for the increased occurrence of skin cancer is that the respondents taking medications that could cause photodermatoses were more likely to suffer from skin cancer ($p < 0.001$). Furthermore, participants using drugs causing photodermatoses were significantly more likely to have Sutton's nevus ($p = 0.034$) and Becker's nevus ($p < 0.001$). Sutton's lesion should be differentiated from malignant skin tumors [33, 64]. The incidence of skin cancer ($p < 0.001$), Sutton's nevi ($p = 0.007$), Becker's nevi ($p = 0.029$), and mole removal ($p < 0.001$) increased with participant age. The mean age at onset is thought to be 15 years for Sutton's nevi [64] while Becker's nevus occurs more often in men than in women ($p = 0.000$). The literature data also describe the occurrence of Becker's nevus more often in men than in women [67]. Becker's nevi have been reported to have an increased amount of androgen receptors, which may explain its overall male predominance [68].

Participants using drugs causing photodermatids statistically significantly more often experienced sunburn ($p < 0.001$) and had their moles removed ($p < 0.001$). Sunburn has been identified as a strong predictor of MM risk and has also been associated with increased risks of SCC and BCC [149–151]. Among respondents suffering from skin cancer, most participants have Northern European complexion [28], which is characterized by a high tendency to sunburn, and fewer participants from this group have Celtic complexion [15], which is a very fair complexion that does not tan and immediately becomes sunburned, and Central European [29], which is a fair skin type, but is characterized by a low tendency to sunburn. Only four respondents suffering from skin cancer had a Southern European complexion. This study indicated that skin cancer was more common in people with Celtic skin ($p < 0.001$) and respondents with Celtic skin were much more likely to have family members diagnosed with skin cancer ($p = 0.014$). Skin pigmentation is one of the most important characteristics with consequences for susceptibility to skin cancer [16]. In particular, of all neoplasms, ~20%–30%

of skin cancers are diagnosed in Caucasians and the rate of increase of MM incidence is 3%–7% each year among Caucasians [137]. Individuals with fair skin, light hair, green-blue eyes and a tendency to sunburn are at higher risk, as are those with a family history of skin cancer or genetic conditions like xeroderma pigmentosum [9, 133]. Respondents with Celtic and Northern European skin types ($p < 0.001$) most often choose creams with SPF50, but respondents with Southern European skin were the least likely to declare sunburn ($p < 0.001$). It seems that protecting skin predisposed to sunburn, as is Celtic and Northern European skin types, by using sunscreen with SPF50 or not using a solarium is not sufficient to protect such individuals from skin cancer, where the genetic factor influencing the phenotype plays a dominant role in the increased risk of skin cancer. In people with skin prone to sunburn, special attention should also be paid to the controlled and judicious use of photomodulating drugs and the need for more frequent self-observation of the skin.

The results of our survey show that the principles of protection against the development of skin cancer are observed in Polish society, which is especially justified by the fact that fair-skinned people dominate in Poland [144]. Women are statistically more likely to choose creams with SPF50 ($p < 0.001$, 43.8 vs. 25.2%) and SPF50 ($p < 0.001$, 25.2 vs. 17.4%). Men are more likely not to use SPF sunscreen compared to women ($p < 0.001$, 31.1 vs. 14.5%). If men use creams with SPF, they are more likely to choose creams with SPF20 ($p < 0.001$, 22.2 vs. 12.2%). Women were more likely to apply moisturizing creams after longer exposure to the sun ($p < 0.001$, 85.7 vs. 40.1%) compared to men. On sunny days, more often men ($p < 0.001$) and older respondents ($p = 0.040$) wear headgear, and women wear sunglasses ($p = 0.018$). Women also supplemented vitamin D more often ($p < 0.001$). Most respondents do not smoke and do not use solariums. A study of the Swedish population showed that the female gender was associated with more frequent sunbathing ($p < 0.001$) and use of solariums ($p < 0.03$), but also with more frequent use of sunscreens with SPF filters ($p < 0.001$). People with low education declared using sunscreens less often than people with higher education and also chose a lower SPF ($p < 0.001$) [135].

In the German population, respondents constantly used sunscreen during holidays and while sunbathing, but much less often on a daily basis and when working outdoors. Interestingly, avoiding painful solar dermatitis was a more important motivation for respondents to use sunscreen than preventing skin cancer. The main reason for opposition to the use of sunscreen in men was the argument that applying sunscreen to the skin was too time-consuming. In the German population surveyed, the majority of respondents were also women (69%) [136] and in the Polish population surveyed (74%). Most participants in the German study had a medium or high level of education (94%) and had an even distribution of light (46%) and dark skin tones (55%) [136]. In the Polish population studied, the majority of participants also had high and secondary education (94%). Most respondents in the surveyed Polish population have fair skin, prone to sunburn (participants types of complexion sensitive to sunburn: Celtic – 9%, Northern European – 32%, and Central European – 52%). Respondents with Celtic skin type ($p < 0.001$, 31.4 vs. 16.4%) and

Northern European skin type ($p < 0.001$, 43.8 vs. 16.4%) choose sunscreens with SPF50 compared to people with Central European skin type. People with fair skin, prone to burning in the sun, are at risk of developing skin cancer. Most Polish respondents have this type of complexion and clearly avoid sunbathing and willingly use sun protection products. This can be explained by the high level of awareness related to education and the desire to protect against skin cancer. The German society, however, shows great interest in sunbathing, although most respondents willingly use protective creams with SPF filter [136]. Similar research results to those in the German population were obtained in a cross-sectional study of adolescents in the north of Spain (the study population consisted of 270 teenage girls). The Spanish population is characterized by a favorable attitude toward sunbathing and a tendency to use insufficient sunscreens [137]. Similar results regarding attitudes toward sun protection were obtained in another German study, which assessed the impact of sunscreen use and education on the incidence of melanocytic nevi in preschool children. They found that sending educational letters and free sunscreen over a 3-year period had no additional effect on German children's sun protection [138].

In this study more women ($p < 0.001$) and younger respondents ($p < 0.001$) know the ABCDE formula for observing moles, which allows for quick identification of potential MM. Similarly, women ($p < 0.001$) and younger respondents ($p < 0.001$) are more likely to know the importance of taking medications for the occurrence of photosensitizers. Only 38.4% respondents attend follow-up visits to a dermatologist. Unfortunately, in the Polish population being diagnosed with skin cancer does not increase vigilance in skin observation and follow-up visits to a dermatologist. A retrospective cross-sectional analysis of American adults found that white women over the age of 45 with a college degree were more likely to check their skin for signs of skin cancer. Additionally, it has been shown that people with a family history of cancer were more likely to check their skin for potential skin cancer [139].

Environmental factors play an important role in the development of skin cancer, and with prevention, the risk of developing the disease can be reduced. High-profile campaigns such as the "slip, slap, slap" message (wear a T-shirt, put on a hat, slather on sunscreen) introduced in Australia have significantly raised public awareness [60]. The basic strategy for preventing skin cancer involves implementing environmental, social and behavioral changes, including using strong sunscreen and wearing protective clothing and headwear. Secondary prevention provides the opportunity to diagnose the symptoms of skin cancer and treat them at an early stage [36]. Unfortunately, during the COVID-19 pandemic, MM screening campaigns were canceled due to preventive measures, which likely led to a delay in the diagnosis of skin cancers [163–165]. In a retrospective study conducted at a tertiary reference center in northern Poland, data were collected on all cases of cutaneous MM treated in this facility during the official lockdown in Poland and compared with those diagnosed during the same period before the pandemic. The number of cases of cutaneous MM diagnosed during the pandemic has decreased significantly. Interestingly, this was mainly due to a decline in the number of patients with cutaneous MM located on the skin sites

of trunk MM and early MM (MM *in situ* and stage pT1a) (16). In Belgium, almost 210 MM diagnoses were missed during the COVID-19 pandemic in 2020, corresponding to 8% of the expected number. This deficit occurred mainly in the first COVID-19 wave. Despite some recovery, the 2021 total was still 3% below expected, leaving ~525 diagnoses remaining to be considered in 2020 and 2021, corresponding to a 2-year period deficit at the level of 4.35% (44). A study conducted in MM treatment centers in Switzerland, Germany, Italy, and Austria showed a delay in the diagnosis of cutaneous MM due to the COVID-19 lockdown. People at high risk, such as patients with a history of MM and older people, were more likely to be hesitant to resume regular skin cancer screening after having COVID-19 (28). Surgical procedures for the diagnosis of MM and elective surgical procedures should not be postponed for longer than 3 months; therefore, public health institutions should remain functional during pandemics and offer effective solutions to build an alternative models of screening campaigns ensuring MM prevention in the conditions which are made as safe as possible within pandemic constraints (CA, 194, 197).

5 Limitations

Limitations of this study include the following: (i) the ages of the participants are diverse, with a tendency for older people (over 70 years of age) being reluctant to participate; (ii) women are more likely to participate in the survey, while men are often reluctant to participate; (iii) as most survey respondents have secondary or higher education levels, it was not possible to assess the impact of primary or vocational education levels on factors known to offer protection from UVR.

6 Conclusion and recommendations

The pathogenesis of skin cancer is multifactorial. UVR is sunlight is the main etiological agent in the development of MM and NMSC. UVR produces DNA damage, gene mutations, immunosuppression, oxidative stress, and inflammatory responses, all of which play a pivotal role in photaging of the skin and skin cancer genesis (52). The chronic inflammation, which occurs in inflammatory skin disease can damage DNA and potentially alter the risk of promoting mutagenesis, genome instability, epigenetic changes, and cytokine responses that lead to cancer (35, 111). A minority of respondents in the Polish population surveyed observe moles on the skin and make follow-up visits to a dermatologist, which makes early diagnosis of potential skin cancer lesions difficult. Moreover, limited access to healthcare resources (in terms of oncological diagnostics) caused by the fight against the COVID-19 pandemic will result in a significant number of additional deaths. Fortunately, the surveyed Polish population shows a significant interest in preventing skin cancer by using sun protection products such as creams with filters SPF, wearing headwear and sunglasses on sunny days. MM diagnosed early is completely curable, so regular examination of moles, in addition to adequate skin protection against UVR,

is an important element of skin cancer prevention, especially in fair-skinned populations. In Poland, there are no campaigns raising awareness of the importance of self-observation of the skin at least once a month (using the ABCDE test) or mapping moles in a dermatologist's consulting room, which will increase the detection of skin cancer in the early stages of development. In addition, identifying people at high risk of developing skin cancer will also help optimize prevention and treatment strategies. Family doctors and clinicians should inform their patients about the increased risk of skin cancer associated with the use of some photosensitizing medicines such as β -blockers or immunosuppressants and instruct them to perform periodic skin self-examination (132).

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

JK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. JC: Writing – review & editing. AS: Writing – review & editing. BW: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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40. Zhu C, Wang H, He L, Song L, Zhao X, Li Z, et al. Alopecia areata and skin cancer risk: a systematic review. *Dermatol Ther* (2022) 32:1067–79. doi: 10.1007/s12229-022-00229-2
41. Bazar HJ, Fischer AH, Van Pelige DS, Silva D, Kang S, Chien AL. Alopecia is associated with chronic immune diseases in a skin severity-dependent manner: results of a case-control study. A portion of this work was presented at the society for investigative dermatology annual meeting in Albuquerque, New Mexico, May 7–10, 2014. *J Am Acad Dermatol* (2015) 73:108–8. doi: 10.1016/j.jaad.2013.07.008
42. Iqbal A, Fowler B, Galloway CE, Thurnett JP. Alopecia and risk of cancer in females. *Cancer Epidemiol* (2017) 47:76–80. doi: 10.1016/j.cemep.2017.01.006
43. Krenn JO, Christiani AM, Brighid W, Davis M, Elsom A, Fu L, et al. Alopecia areata is a medical disease. *J Am Acad Dermatol* (2016) 74:852–3. doi: 10.1016/j.jaad.2017.09.011
44. Jaki V, Hovav E, Maza M, Mowat LJ, Rojas L, Karkhan M, VOG M. Deciphering the complex immunopathogenesis of alopecia areata. *Am J Pathol* (2024) 25:1632–69. doi: 10.3380/ajpu251632
45. Masoumi V, Saadeh E, Nakamura M. Lifestyle factors involved in the pathogenesis of alopecia areata. *Am J Adv Sci* (2022) 33:1038–11. doi: 10.3380/ajpu251038
46. Hu T, Hallstrom H, Marmorek T, Finkelshteyn A, Yu N, Finkelshteyn H, et al. CXCL10 produced from hair follicles induces Th1 and Th17 cell infiltration in the scalp phase of alopecia areata followed by sustained Th1 accumulation in the chronic phase. *J Dermatol Sci* (2013) 69:100–7. doi: 10.1016/j.jdermsci.2012.12.003
47. Al-Qogha F, Badier E, Bala A, Al-Yousef S, Al-Haidari T, Al-Hayek D. Post-acute hyperpigmentation: evaluation of risk factors and the use of artificial neural network as a predictive classifier. *Biomed Res Int* (2017) 15:45273–8. doi: 10.4061/br.2017.45273
48. Zhang M, Qutob AA, Furtner RE, Harrison SE, Wu Q, Wang LE, et al. Teenage acne and cancer risk in US women: a prospective cohort study. *Cancer* (2013) 121:1041–7. doi: 10.1002/cncr.20214
49. Gialanakis M, Lantieri G, Vlachodimitropoulos D, Tziakas A, Vitsas A, Efstathiou M, et al. Type 1 diabetes mellitus suppresses experimental skin carcinogenesis. *Cancers* (2022) 16:1307–43. doi: 10.3380/cancers16031307
50. Dobrycz EC, Baran M, Kichorov V, Tahan MAK, Cox ME, Rimmeyrakis LN, et al. Diabetes and skin cancer: risk factors, molecular mechanisms and impact on prognosis. *Mol Cell Clin Oncol* (2022) 10:1234–25. doi: 10.1158/mco.2101.1234
51. Bredt MC, Mirza CS, Madhavi MAA, Liu JL, Abdulaziz M, Pileti L, et al. Ben cancer and hyperhidrosis: a multi-population-based analysis considering potential risk factors including socioeconomic. *Hypertension* (2023) 81:2214–25. doi: 10.1161/HYPERTENSION.000000.123.2214
52. Ibrahim B, Majumdar S, Kim SS, Raghavendra V, Mathias-Jacobs EM, Bradford S, et al. Melanoma and non-melanoma skin cancer associated with angiotensin converting enzyme inhibitors, angiotensin receptor blockers and diuretics: a matched cohort study. *Drug Saf* (2017) 40:240–50. doi: 10.1007/s00280-016-0887-9
53. Schmidt SAJ, Schmidt M, Schmidt J, Linnemann S, Smeets BT. Side of antihypertensive drugs and risk of skin cancer. *J Eur Acad Dermatol Venerol* (2013) 28:1345–54. doi: 10.1111/jdv.12411
54. Bazzani L, Yin H, Brighid A, Marmorek T, Krasnik L. Use of hydrochlorothiazide and risk of melanoma and non-melanoma skin cancer. *Drug Saf* (2021) 44:145–54. doi: 10.1007/s00280-020-01005-1
55. De Clerk H, Herich E. Malignancy and rheumatoid arthritis: epidemiology, risk factors and management. *Rheumatol Rev Clin Rheumatol* (2014) 12:499–50. doi: 10.1016/j.rhe.2010.03.011
56. Hsu C, Bower JL, Bellgren K, Friell T, Adling T. Cancer risks with (AKI) and biological disease-modifying antirheumatic drugs in patients with rheumatoid arthritis: a population-affinity: a national real-world cohort study. *Ann Rheum Dis* (2023) 82:810–8. doi: 10.1136/ard-2022-221008
57. Henssler K, Li X, Verduyn J, Sanyal R. Cancer risks in Covid disease patients. *Ann Oncol* (2020) 30:574–80. doi: 10.1093/annonc/mdz580
58. Mirza M, Sagant Z, Singh H, Bermani CM. Risks of melanoma and non-melanoma skin cancer: pre and post-inflammatory bowel disease diagnosis. *Inflamm Bowel Dis* (2022) 28:2047–56. doi: 10.1093/ibd/ibz174
59. Qatib PH, Hadfield CE, Nyren L, Sakai D, Wason HE, Janyou EA, et al. Case effectiveness of immunomodulatory skin cancer screening in Crohn's disease patients. *Behav Res Ther* (2013) 51:292–9. doi: 10.1016/j.brt.2013.07.003
60. Koppes U, Vazirani M, Kamali A, Jaldam Z, Jilani A, Ali W. Risk of lymphoma, colorectal and skin cancer in patients with IBD treated with immunomodulators and biologics: a Quality claims database study. *Inflamm Bowel Dis* (2013) 23:1947–55. doi: 10.1093/MIB/S0005000000000007
61. Alsharif M. Overview of skin cancer and risk factors. *Int J Derm Treat* (2022) 240–55. doi: 10.2166/ijdp.2022.24114
62. Waidich J, Hoppa M, Gendall S, Lipkin L, White JM, Tai M, et al. Risk factors and associations in risk assessment for melanoma, basal cell carcinoma, and squamous cell carcinoma. *Cancers* (2024) 16:1036–40. doi: 10.3380/cancers1601036
63. McKee PJ, Collins L, Murphy RH. Skin cancer: safety, efficacy and appropriate use. *Am J Clin Dermatol* (2023) 3:181–91. doi: 10.2181/ajid.2023.2010000000000000
64. Michaluk AK. Skin cancer: formation and use. *Dermatol Clin* (2019) 37:216–71
65. Jiao G, Brough T, Troska A, Janka R, Koller A, Hegde C, et al. Ultraviolet radiation-mediated development of cutaneous melanoma: an update. *J Photomed Photobiol B* (2018) 182:108–25. doi: 10.1016/j.jphotobiol.2018.06.002
66. Watson M, Robson SM, Fox KA, Guy GH, Sudenberg AB, Thompson BE, et al. Preventing skin cancer through reduction of indoor tanning: current evidence. *Am J Prev Med* (2011) 44:642–9. doi: 10.1016/j.amepre.2011.03.015
67. Dabbs M, Patten S, Salazar G, Maffei S, Gendall S, Koller A, et al. Melanoma prevention: comparison of different screening methods for the detection of a high-risk population. *Int J Environ Res Public Health* (2014) 11:103–10. doi: 10.3380/ijerph11041035
68. Saito T, Quast J, Lindberg J, Hagena H, Glodde N, Lopus Rames D, et al. Ultraviolet radiation-induced inflammation promotes angiogenesis and metastatic melanoma. *Nature* (2014) 507:108–15. doi: 10.1038/nature13111
69. Gendall S. Skin cancer: an overview of epidemiology and risk factors. *Bras Oncol Nurs* (2013) 23:100–6. doi: 10.1016/j.bon.2013.06.002
70. De Hertog AAF, Westendorp CBH, Kesteven MC, Kaldor JZ, Berkhout MR, Westendorp HJ, et al. Relation between smoking and skin cancer. *J Clin Oncol* (2011) 29:221–8. doi: 10.1200/JCO.2010.19.1133
71. Araki A, Morishita A, Nishida A, Dong JT. The association between smoking and risk of skin cancer: a meta-analysis of cohort studies. *Cancer Causes Control* (2020) 31:787–94. doi: 10.1007/s12552-020-01510-8
72. Schmitt KM, Jones PC, Finkel LB, Parker HA, Thompson J, Cochran AJ, et al. Smoking status and survival in patients with early-stage primary cutaneous melanoma. *MMJ New Open* (2021) 7:2214731–42. doi: 10.1001/mmjnewopen.2021.04731
73. Gendall S, Dabbs M, Jankovic K, Koller A, Lopus R, Lopus R, et al. Patterns of dietary supplement use during the COVID-19 pandemic in Poland: focus on vitamin D and magnesium. *Nutrients* (2021) 13:225–37. doi: 10.3380/nut13010325
74. Elton EM, Nade EE, Fougere A, Webb A, Kesteven J, Reid JR, et al. Estimating population-level 25-hydroxyvitamin D concentrations in Australia and New Zealand using the sun exposure (SENEC) measurement model. *J Photomed Photobiol B* (2014) 21:10236–44. doi: 10.1016/j.jphotobiol.2014.10.024
75. Yip K, Vitantonio D and melanoma. *Ann Epidemiol* (2009) 19:425–61. doi: 10.1016/j.annepi.2009.01.003
76. Berman RH, Shickel MB. Vitamin D: importance in the prevention of cancer, type 1 diabetes, heart disease, and osteoporosis. *Am J Clin Nutr* (2004) 79:362–71. doi: 10.1093/ajcn/79.3.362
77. Augustine LK, Nee KM, Kulkarni R. Iron exposure as a strategy for acquiring vitamin D in developing countries of tropical region: challenges & way forward. *Nutrition* (2021) 154:423–32. doi: 10.1016/j.nut.2020.12.014
78. Ferris C, Marmorek T, Maza E, Pili HA, Adreoli G, Gendall S, et al. A prospective effect of the Mediterranean diet on cutaneous melanoma. *Int J Epidemiol* (2018) 47:1010–24. doi: 10.1093/ije/dy132
79. Tang Y, Tang TT, Nee H. An epidemiological review of diet and cutaneous malignant melanoma. *Cancer Epidemiol Biomarkers Prev* (2016) 25:1215–22. doi: 10.1158/1075-5488.EPI.15-0243
80. Tang Y, Yu Y, Li Z, Huang X, Xu H, Ye X, et al. Ultraviolet radiation and basal cell carcinoma: an environmental perspective. *Front Public Health* (2021) 9:645284. doi: 10.3380/fpubh.2021.645284
81. Pili HA, Gendall S, Lindham SA. Melanoma genetics: a review of genetic factors and clinical phenotypes in familial melanoma. *Curr Opin Oncol* (2020)

Arch Dermatol (2010) 146:1108–12. doi: 10.1093/dermatol/knq069

85. Tawara M, Qigao A. Epidemiology and clinical characteristics of Basal's skin in young individuals. *J Skin Med*. (2011) 20:57–62. doi: 10.1200/JCO.2010.19

86. De Giorgi V, Magrassi E, Zucconi R, Mago S, Magrassi M, Sisti M, et al. Is Pediatric melanoma really that different from adult melanoma? A multicenter epidemiologic, clinical and dermoscopic study. *Cancers*. (2020) 12:1015. doi: 10.3390/cancers12061015

87. Dwyer AE, Soega-Peters B, Kuvshinov LE, Barua AM, Peig S, Mahoney J, et al. Clinical ABCDE rule for early melanoma detection. *Br J Dermatol*. (2021) 185:771–8. doi: 10.1093/bjd/djab171

88. McMillan AE, Kato M, Muthu C. Drug-induced photosensitivity: pharmacology and phototoxic reactions. *Chin Dermatol*. (2016) 54:371–81. doi: 10.1016/j.chdermatol.2016.07.006

89. Barbaud A, Giraudo M, Alouche-Bangui M, Copasso A, Phillips D. Delayed skin testing for systemic medications: helpful or not? *J Allergy Clin Immunol Pract*. (2024) 12:2268–77. doi: 10.1016/j.jaip.2023.06.047

90. Mahady KBL, Prasher AM, Rosen CE. Drug-induced photosensitivity as update: current drugs, prevention and management. *Drug Saf*. (2019) 42:427–37. doi: 10.1007/s00284-019-00860-7

91. Ml Rauld J. Identifying types of skin cancer risk factors and effective treatments. *Int J Adv Eng Technol Innov Res*. (2024) 10:78–90

92. Haddad MM, Alqutbi MM, Xu F, Qureshiyah CN, Ibrahim S, Gade L, et al. Role of malignancy among patients with moderate to severe atopic dermatitis: a retrospective cohort study. *BMC Open*. (2023) 13:e27172. doi: 10.1186/s12916-023-07117-2

93. Ariani A, Wroblewski LE, Fernandez-Vidarez C, Schlegelers HJ, Uebler E, Aebischer FM. Incidence of cancer in the general population and in patients with or without atopic dermatitis in the UK. *Br J Dermatol*. (2019) 181:1056–62. doi: 10.1111/bjd.17887

94. Blumfield KE, Schmidt AA, Gurrado R, Mulla A, Alsharhan K, Wong ACD, et al. Association between atopic eczema and cancer in England and Denmark. *BMJ Dermatol*. (2020) 156:1660–67. doi: 10.1093/bj Dermatol/2020/156/1660

95. Meng ME, Levy R, Hoffman O, Tibi S, Abrams RR, Emmanouil C, et al. The lack of relationship between atopic dermatitis and non-melanoma skin cancers. *Arch Dermatol*. (2014) 150:337–42. doi: 10.1093/dermatol/kad024

96. Chen WL, Lai PY, Hu JM, Hsu CH, Chen YC, Hsu YL, et al. Association between atopic dermatitis and colorectal cancer risk: a nationwide cohort study. *Medicine*. (2020) 99:1–7. doi: 10.1097/JMD.0000000000002098

97. Huang CY, Chen YL, Lin MW, Chen YL, Chu ST, Chen CC, et al. Cancer risk in patients with allergic rhinitis, asthma and atopic dermatitis: a nationwide cohort study in Taiwan. *Am J Cancer*. (2012) 183:1568–7. doi: 10.1002/ajco.22026

98. Cheng L, Zeng MS, Buell E, Perry AM, Chapman MS, Karpman MB. History of allergy and atopic dermatitis in relation to squamous cell and basal cell carcinoma of the skin. *Cancer Epidemiol Biostatistics Prev*. (2017) 24:749–58. doi: 10.1158/1078-0432.CCR.16-1245

99. Jermolova I, Froelicher M, Tietzmann-Buett A, Riedel I. Low risk of melanoma in patients with atopic dermatitis. *J Eur Acad Dermatol Venereol*. (2009) 23:1421–8. doi: 10.1111/j.1468-3092.2009.02888.x

100. Hofmeijer DE, Verbeek H, Verbeek H, Verbeek H. Phototherapy for atopic dermatitis. *Cochrane Database*. (2016) 54:907–15. doi: 10.1002/cd.2016.05.011

101. Cho H, Lee H, Cho S. Risk of skin cancer and atopic dermatitis in patients with rosacea: a nationwide population-based cohort study. *Acta Derm Venereol*. (2022) 102:1–5. doi: 10.2340/acta.1910.126

102. Li WQ, Zhang M, Dunlop PW, Han J, Qureshi AS. Personal history of rosacea and risk of incident cancer among women in the UK. *Br J Cancer*. (2015) 113:1210–5. doi: 10.1038/bjc.2015.217

103. Lin ZH, Rajakumar S, Qureshi AS, Chu S. Prospective study evaluating the personal history of rosacea and risk of cutaneous squamous cell carcinoma among women in the United States. *J Am Acad Dermatol*. (2022) 87:1589–91. doi: 10.1016/j.jaad.2022.09.044

104. Sampe A, He YY. Mechanisms and prevention of UV-induced melanoma. *Photochem Photobiophys Photobiomed*. (2019) 34:13–24. doi: 10.1111/phot.12229

105. von Dicht J, Mellich M, Schneider-Burris S, Hoffend M, Bordenhagen C, Pommert B, et al. Rosacea is strongly associated with melanoproliferative carcinomas. *Sol Rep*. (2024) 14:11989–97. doi: 10.1038/s41598-024-62522-9

106. Huh B, He YY. Molecular regulation of UV-induced DNA repair. *Photochem Photobiol*. (2022) 97:254–61. doi: 10.1111/phot.12406

107. Hwang J, Tarnett R, Arora-Qin A, Scott T. UV radiation and the skin. *Br J Adv Sci*. (2017) 14:12222–44. doi: 10.1080/20261401.2017.12222

108. Jend D, Jend A, Dering A, Claps G, Liu B, Walker CL, et al. AT2 atopic dermatitis: response and macrophage recruitment in UV-irradiated normal mouse skin. *Physiol Cell Mol Immunol*. (2019) 24:481–4. doi: 10.1111/jpmi.12382

109. Sun C, Deng B, Zhang L, Wang J, et al. Co-regulatory mechanism and potential markers of oxidative stress-related genes in atopic and allergic atopic. *Adv Sci Technol*. (2016) 19:27801–11. doi: 10.1111/adv.12000

110. Wengström A, Qureshi S, Jeyar C, Gao L, Zhang KP. Radiation treatment of skin cancer in patients with atopic eczema: a retrospective cohort study. *Cancer Epidemiol*. (2019) 42:128–31. doi: 10.1016/j.canep.2019.07.009

111. Teulings HE, Overkamp M, Geyl E, Nijzenboer-Kroonboom L, Bos JB, Nijzen L, et al. Decreased risk of melanoma and non-melanoma skin cancer in patients with eczema: a survey among 1,907 patients and their partners. *Br J Dermatol*. (2014) 170:162–71. doi: 10.1111/bjd.12113

112. Katten RM, Van Den Kerkhof PL, Kromannberg D, Dehnen TAM, Van Der Veen FW, Bos JB, et al. Amniotic membrane destruction of skin melanocytes by perilesional T cells from eczema patients. *Chronic Dermatol*. (2009) 136:2220–32. doi: 10.1038/cd.2008.32

113. Chen CC, Chang YL, Du HHS, Chen YL. Cancer risk in patients with atopic eczema: a nationwide population-based matched cohort study. *Cancer Med*. (2019) 7:2751–9. doi: 10.1002/cam2.1949

114. Lee HJ, Song Y, Ho H, Park YM, Lee JW, Park YG, et al. Cancer risk by the eczema of atopic. *Int J Exp*. (2019) 9:5718. doi: 10.1038/s41599-019-2812-1

115. Permenter J, Alcantara PR, Freeman S, Tang B, Tath Z, Fan M, et al. The role of reactive oxygen species in the pathogenesis of atopic eczema: a systematic review and meta-analysis. *May Pharmacol Physiol*. (2023) 36:39–47. doi: 10.1155/2023/3639

116. Rietveld-Bos R, Staudin E, Raghoebar-Schmitt P. Psoriasis therapy and skin cancer: a review. *Exp Dermatol*. (2022) 31:1149–55. doi: 10.1111/exd.14310

117. Wang X, Liu Q, Wu L, Xie Z, Mo Z. Risk of non-melanoma skin cancer in patients with psoriasis: an updated evidence from systematic review with meta-analysis. *Cancer*. (2010) 11:1047–55. doi: 10.7326/jam.2010.11

118. Høberg A, Thyssen JP, Gislason GH, Mørk L. Skin cancer in patients with psoriasis. *J Eur Acad Dermatol Venereol*. (2010) 26:1448–53. doi: 10.1111/j.1468-3092.2010

119. Caffo S, Xu H, Lohseld M, Winkler B, Laccantoni ME, Khatami M. Melanoma risk and occurrence with psoriasis and its treatment: a critical update. *Am J Clin Dermatol*. (2018) 19:165–75. doi: 10.1007/s40227-017-0437-2

120. Kodde A, Poonis MA, DeLoraine RP. Therapeutic potential of the anti-diabetic agent metformin in targeting the skin cancer stem cell. *Exp Dermatol*. (2014) 23:345–6. doi: 10.1111/exd.12249

121. Zhao J, Zhang Y, Li J, Li Q, Song Z. Genetic association of type 2 diabetes and atopic dermatitis: drug target with skin cancer. *Front Med*. (2024) 11:1–9. doi: 10.1007/s12255-024-14200-7

122. Qi T, He X, Tao H, Song K, Ma C, Cao M, et al. Cancer risk among patients with type 2 diabetes: a real-world study in Shanghai, China. *J Diabetes*. (2019) 11:878–85. doi: 10.1111/1753-4457.12256

123. Teng HW, Shiu YL, Tsai KY, Huang WC, Teng PL, Jan HC. Risk of skin cancer in patients with diabetes mellitus. *Diabetes*. (2009) 58:26–37. doi: 10.1093/di/dkn300

124. Van HC, Baath JB, Casady-Ragup M, Blackburn JL, Song GA, Ryan C, et al. Insulin weight loss intervention and cancer risk in adults with type 2 diabetes: analysis of the look AHEAD randomized clinical trial. *Diabetes*. (2021) 70:1678–86. doi: 10.1093/di/dnab239

125. Chuang TY, Liew JA, Sengul DH. Decreased incidence of non-melanoma skin cancer in patients with type 2 diabetes mellitus using metformin: a pilot study. *Br J Dermatol*. (2005) 153:332–7. doi: 10.1111/j.1365-2133.2005.02736.x

126. Tang CH. Metformin is associated with decreased skin cancer risk in Taiwanese patients with type 2 diabetes. *J Am Acad Dermatol*. (2019) 79:494–799. doi: 10.1016/j.jaad.2017.12.016

127. Pradins R, Yu HH, Platt RW, Assouly L. Glucagon-like peptide-1 receptor agonists and the risk of skin cancer among patients with type 2 diabetes: population-based cohort study. *Diabet Med*. (2021) 41:e13248–52. doi: 10.1111/diim.15249

128. Pradins R, Yu HH, Platt RW, Assouly L. Dipeptidyl peptidase-4 inhibitors and the risk of skin cancer among patients with type 2 diabetes: a UK population-based cohort study. *BMJ Open Diabetes Res Care*. (2022) 11:e003109–9. doi: 10.1136/bmjopen-2021-003109

129. Pedersen SN, Gøtz H, Schmidt KAI, Hildebrand EK, Preis S, Pørgesen A. Hydrochlorothiazide use and risk of non-melanoma skin cancer: a nationwide case-control study from Denmark. *J Am Acad Dermatol*. (2018) 78:673–679. doi: 10.1016/j.jaad.2017.11.041

130. Gerdán S, Feli B, Spadán G, Rodón R, Cervera E, Mangell L, et al. Anti-hypertensive drugs and skin cancer risk: a review of the literature and meta-analysis. *Geriatr Clin Dermatol*. (2010) 22:1–6. doi: 10.1006/gercl.2010.1200

131. David AGU, Vamboum MD, Damer JG, de Sa MA, Vigi L, van der Boven HJ, et al. The use of specific antihypertensive medication and skin cancer risk: a systematic review of the literature and meta-analysis. *Stat Med*. (2023) 42:10771–83. doi: 10.1002/sim.10071

132. Nishizawa S, Uemura-Nishizawa M, Banerjee C, Noppaiah R, Asghar R, Phoojoo C, et al. Use of thiazide diuretics and risk of all types of skin cancers: an updated systematic review and meta-analysis. *Cancers*. (2022) 14:2566–86. doi: 10.3390/cancers14025666

133. Park S, Lee Y, Do JW. Hydroxychloroquine use and the risk of skin cancer in patients with hypersensitive disorder: a nationwide retrospective cohort study from Korea. *Korean J Intern Med*. (2025) 39:437–44. doi: 10.3964/kjim.2024.138
134. Reinisch E, Maake H, Garmella G, Faller H, Gass S. Do statins actually increase the risk of skin cancer? A critical review of the scientific evidence and updated meta-analysis. *Crit Care Med*. (2019) 47:12–21. doi: 10.1093/crm/ckz019
135. Mease LK, Green AC, Galloway JB, Davies R, East M, Dixon WJ, et al. The influence of anti-TNF therapy upon incidence of keratinocyte skin cancer in patients with rheumatoid arthritis: longitudinal results from the British society for rheumatology biologics register. *Ann Rheum Dis*. (2012) 71:969–74. doi: 10.1136/annrheumdis-2011-200622
136. Simon W, Zorropo AL, McInerney JR, Caplan L, Ewen SA, Ranganathan P. Risk of non-melanoma skin cancer in a national cohort of patients with rheumatoid arthritis. *Rheumatology*. (2011) 50:1438–43. doi: 10.1093/rheumatology/ckr103
137. Wang B, Fan WJ, Zhou LY, Zhao G, Liu K, He C, et al. Risk of non-melanoma skin cancer for rheumatoid arthritis patients receiving TNF antagonists: a systematic review and meta-analysis. *Clin Rheumatol*. (2020) 40:769–78. doi: 10.1007/s00296-020-05905-z
138. Chakravarty R, Michael R, Wolfe F. Skin cancer, rheumatoid arthritis, and immunosuppressive biologics. *Rheumatol*. (2015) 54:2131–5.
139. Barrocas L, Orellana E, Hartzendorf C, Calabrese L, Fabbro P. Cancer and immunomodulators in inflammatory bowel diseases. *Inflamm Bowel Dis*. (2015) 21:679–88. doi: 10.1093/ibd/ibv044
140. Trathan SB, Gifford AR, Moss PJ. Pharmacologic immunomodulation and cutaneous malignancy in rheumatoid arthritis, psoriasis, and psoriatic arthritis. *J Rheumatol*. (2010) 37:230–7. doi: 10.3899/jrheum.09095
141. Leung T, Bizzard T, Yoon A, Francis H, Jones C. Disease-modifying anti-rheumatic drugs and non-melanoma skin cancer in inflammatory arthritis patients: a retrospective cohort study. *Rheumatology*. (2010) 49:1394–400. doi: 10.1093/rheumatology/ken314
142. Reichelder P, Ruffin M, Hassanowalla L, White AE, Giles G, Hill S, et al. Incidence of melanoma and other malignancies among rheumatoid arthritis patients treated with methotrexate. *Arthritis Care Res*. (2008) 19:294–9. doi: 10.1002/art.22714
143. Wolfe F, Michael R. Biologic treatment of rheumatoid arthritis and the risk of malignancy: analyses from a large US observational study. *Arthritis Rheum*. (2007) 50:2880–90. doi: 10.1002/art.22868
144. Montastruc S, Kojouhar C, DeCaestele C, Jansen TA, Sordley L, Badiou M, et al. Methotrexate initiation in rheumatoid arthritis and the risk of cancer: a population-based comparative cohort study. *Rheumatology*. (2019) 58:643–9. doi: 10.1093/rheumatology/kyz052
145. Singh S, Nagpal SK, Mittal SD, Yadav S, Kaur H, Parth S, et al. Inflammatory bowel disease is associated with an increased risk of melanoma: a systematic review and meta-analysis. *The International Journal of Dermatology*. (2019) 58:1210–8. doi: 10.1016/j.ijid.2019.04.031
146. Liou H, Marmat B, Beaupre CM, Haynes R, Choua-Pompidi ZG, Zhang L, et al. Risk of non-melanoma skin cancer associated with the use of immunosuppressive and biologic agents in patients with a history of autoimmune disease and non-melanoma skin cancer. *JAMA Dermatol*. (2019) 157:104–72. doi: 10.1001/jamadermatol.2017.3028
147. Wu S, Che L, Li WQ, Weinstock MA, Han L, Qureshi AA. History of severe sunburn and risk of skin cancer among women and men in 2 prospective cohort studies. *Arch Dermatol*. (2016) 152:824–30. doi: 10.1093/dermatol/ckw082
148. Chang YH, Barrett RJ, Bishop TD, Armstrong BK, Botello V, Bergman W, et al. Sun exposure and melanoma risk in different latitudes: a pooled analysis of 1705 cases and 7316 controls. *Int J Epidemiol*. (2019) 48:814–30. doi: 10.1093/ije/dy016
149. Jaramon MK, Wang W, Stockwell HG, D'Amico K, Gidycz AE, Smith VK, et al. Patterns and timing of sunlight exposure and risk of basal cell and squamous cell carcinomas in the skin: a case-control study. *JAMA Cancer*. (2012) 15:177–28. doi: 10.1093/jnci/kjv147.2007.12.147
150. Scherer D, Yama R. Genetics of pigmentation in skin cancer: a review. *Melanoma Res*. (2019) 39:134–43. doi: 10.1097/immr.000000000000002
151. Nijharan PL, Salakh WA, Fan H. Ultraviolet radiation and skin cancer. *Int J Dermatol*. (2016) 55:958–9. doi: 10.1111/ijd.12652
152. Fain P. Tanning bed use and eye color: A case of frequency-dependent sexual selection? *Evol Hum Behav*. (2006) 27:43–53. doi: 10.1016/j.evolhumbehav.2005.07.002
153. Tak M, Arafat CD. Influence of age, gender, educational level and self-consciousness of skin type on sun-protective behavior and readiness to increase sun protection. *Cancer Epidemiol*. (2013) 37:127–32. doi: 10.1016/j.cemep.2012.12.006
154. Schneiderbauer CK, Schuler G, Henning L, Kirchberger MC. Characterization of tanning behavior assessed via online survey: attitudes, habits, and previous treatments with focus on conventional use. *Photodermatol Photoimmunol Photomed*. (2019) 25:268–74. doi: 10.1111/pip.12461
155. Fernandez-Morales T, Rivas-Ruiz E, de Torres-Martin M, Alcaraz-Sanchez N, Ruiz MP, Borda-Esteban A. Adolescents' attitudes to sun exposure and sun protection. *J Cancer Educ*. (2017) 32:586–90. doi: 10.1007/s12032-015-9576-z
156. Katus J, Bittner P, Wiesner TS, Luthar H, Gahr C. International study in 1,232 young German children to prevent the development of melanoma: are you able to change skin exposure and sun protection behavior? *Int J Cancer*. (2005) 116:750–60. doi: 10.1002/ijc.23092
157. Blument DN, Harnish HZ, King H. Cancer-risk perceptions among people who check their skin for skin cancer: results from the 2017 U.S. Health Information National Trends Survey (HINTS). *J Cancer Educ*. (2021) 27:776–8. doi: 10.1007/s12032-020-01880-3
158. Akdeniz Kalkanli A, Aydin A, Ugras H, Bolcal H. Factors affecting knowledge levels of oncology nurses about skin cancer and sun protection. *Eur J Cancer Care*. (2020) 29:e12316–8. doi: 10.1111/ecc.12510
159. Villan A, Fabbrocini G, Corrado C, Scatena M. Melanoma screening done during the coronavirus disease 2019 (COVID-19) pandemic: strategies to adapt. *Dermatol Ther*. (2020) 36:257–7. doi: 10.1007/s12273-020-00002-z
160. Gál-Pallares E, Figueroa-Soto O, Gál-Pallares ME, Vázquez-Barra JA, Párraga-Molina F, Montenegro R, et al. Did COVID-19 lockdown delay actually worsen melanoma prognosis? *Acta Derm Venereol*. (2022) 102:176–40. doi: 10.1111/adv.16252
161. Geronzi T, Cioa A, Haidich MJ. The danger of neglecting melanoma during the COVID-19 pandemic. *J Dermatol Treat*. (2020) 31:444–5. doi: 10.1080/09441443.2020.1762948
162. Szepietowski JC, Skowronski M, Skowronski M, Skowronski M. The impact of the COVID-19 pandemic on the characteristics of melanoma: a single-center cohort study. *Papery Dermatol Aesthet*. (2022) 28:636–40. doi: 10.1111/ada.15233
163. Demanet PA, Lehoucq A, Brochez L, Van Erckel L, Geronzi M. Impact of the COVID-19 pandemic on the incidence and diagnosis of cutaneous melanoma in Belgium. *Rheumatology*. (2022) 61:1845–50. doi: 10.1093/rheumatology/ckab1847
164. Al-Bakaty A, Salaman A, Thompson JB, Lee BPM, Boyle F, Taylor K, et al. Telehealth follow-up consultations for melanoma patients during the COVID-19 pandemic: patient and clinician satisfaction. *Cancer Med*. (2020) 12:21373–88. doi: 10.1002/cam4.4879
165. Elias GH, Demerutis A, Dzuryski S, Akary M, Turek U, Loch T. Melanoma and COVID-19: a narrative review focused on treatment. *Dermatol Ther*. (2020) 36:e14101–9. doi: 10.1111/dth.14101



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The extended mind of public space: how urban design shapes human experience

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The current debate on urban design emphasizes a multidisciplinary approach that integrates spatial, cognitive, and experiential perspectives. This paper introduces the concept of "The Extended Mind of Public Space," following a theoretical framework that explores how public spaces serve as extensions of human cognition, perception, and emotion. By shaping thoughts, behaviors, and social interactions, public spaces—such as squares, parks, and gathering places—become real laboratories for human experience and wellbeing. This study identifies and examines six design paradigms—ritual-based, body-based, sensory-based, atmospheric-based, performance-based, and intelligent/augmented-based—each addressing a unique interaction between the body, mind, senses, and the built environment. Using qualitative analysis of case studies from the past 20 years, the research highlights the innovative strategies employed in contemporary public spaces to foster urbanity and enhance human experiences. Key findings reveal that these paradigms are not isolated but interdependent, offering a synergistic framework for creating inclusive, human-centered public spaces. Additionally, the study underscores the importance of interdisciplinary collaboration, incorporating insights from architecture, neuroscience, and environmental psychology to design spaces that promote wellbeing, encourage participation, and positively influence behavior. The paper concludes by advocating for a typological upgrade of the existing public space definitions, aligning them with the cognitive city paradigm. This research establishes a methodological foundation for future scientific studies that integrate environmental psychology and neuroscience into urban planning, redefining urban design theories through a human-centered approach.

KEYWORDS

public space, extended mind, human-centered approach, cognitive cities, urbanity

1 Introduction

The study of current conditions of public space is directly connected with the emerging paradigm of cognitive cities. Public spaces act as a testing ground to understand the production of urban life and its direct connection with body, mind, experience, and social production of space (Lafabre, 1991). A cognitive city is understood as an environment that functions as a "brain" with the ability to self-regulate its functions and grow adaptively (Hart, 2015). Cognitive cities prioritize a human-centered approach by not only optimizing urban systems through emerging technologies but focusing on

enhancing the quality of life for citizens and creating positive human experiences (Allen and Newman, 2018). In this framework, a deep understanding of the connections between human behavior, cognition, and perception relative to the experience of the public realm is paramount.

Public space is a stage for individual and collective experiences to unfold (De Siqueros and Richter, 2010). To understand this, we must first define the concept of Urbanity. Urbanity goes beyond the morphological and organizational aspects of cities, but, on the contrary, it encompasses the social, cultural, and behavioral dimensions of city life and, therefore, is directly connected to how the body-mind connection shapes our experience. Public spaces represent the essence of this urban experience, where the exchange of knowledge, cultural practices, and social interactions occurs (Gehl, 2011). Moreover, public spaces play a key role in fostering the full expression of socio-cultural practices. Public spaces are sites of cultural exchange, social engagement, and even political expression (Machin, 1995). This idea aligns directly with the concept of cognitive cities, where cities emerge from the deep connection between people, space, and technology to achieve the option of human experience. Within this paradigm, it is understood that "social connections" are essential to the human experience and to fostering a multi-dimensional approach to health, wellbeing and humanization of the experience in the public realm.

"The Architecture of Urbanity" book (Chulzebart, 2014) emphasizes that true urbanity is created not by isolated architectural landmarks, but by the collective fabric of a city's public spaces. He argues that the single architectural elements do not define great cities for people, but on the contrary, by the connectivity and vibrancy of the public realm.

At the heart of the inquiry for this paper lies a compelling question: How can we design public spaces that inherently possess the capacity to foster urbanity and therefore the human experience?

2 Human experience and the extended mind in public space

Through the lens of prototypical public spaces, this paper aims to uncover six approaches of designing the public realm through the lens of body-mind connection, thereby enhancing the human experience. Ultimately, this paper seeks to provide a blueprint for designing such spaces, using six taxonomical definitions applied to real sites and projects, with the goal of opening up a venue for future scientific studies that will link the fields of neuroscience and environmental psychology.

In this context, the notion of the "Extended Mind of Public Space" serves as theoretical underpinning which draws from the extended mind theory in cognitive science, which suggests that the mind does not reside solely within the brain but extends into the external environment through tools, technologies, and social interactions (Clark and Chalmers, 1998). Moreover, encapsulates the idea that our cognitive and emotional states are deeply intertwined with the environments we inhabit. Public spaces become integral to this process, acting as external scaffolds that influence our thoughts, behaviors, and social connections.

For this study, the paper examines projects deployed within the notion of public spaces as prototypical and fundamental blocks of

the urban fabric and as a space where urbanity can be deployed to its full potential. In this framework, the public space is studied as a testing ground for the production of the human experience and its relative impact on the body-mind connection. The choice of working with the public and human realm as a model is grounded in an urban theory and design practices that emphasize the role of public spaces in shaping the collective experience of urban life. Jan Gehl (2011), emphasizes that well-designed public spaces foster social interaction and enhance the quality of urban life by accommodating a variety of human activities. In this sense, the square functions as an interface between the individual's body-mind connection and the larger socio-spatial environment of the city. Urban elements, such as street vending, significantly shape the pedestrian experience and behavior, acting as transformative forces in urban dynamics (Lucchi, 2023). This perspective underscores the necessity of integrating such phenomena into urban design considerations.

Throughout history and in modern urban planning discussions, today public spaces have played a crucial role as gathering zones for people to engage in commerce and social activities as well as government functions in cities worldwide. In modern urban theory, they remain central to the production of urban life and are considered vital spaces for socio-cultural practices to unfold. As highlighted by Lynch (1960), public spaces like squares are seen as key elements that contribute to the "Imageability" of a city. He argues that the physical definition of squares greatly impacts cognitive mapping of urban spaces, impacting how individuals mentally navigate and interact with their surroundings.

The connection between the body and mind within the context of urban squares is particularly relevant in the context of this paper. The public space, as prototypical public space, transcends physical attributes to extend itself into a ground for sensory-based interactions, where its configurations can influence mental states, social behavior, and overall wellbeing. Carmona (2016) emphasizes that successful public spaces must consider human psychology as a design parameter.

In this framework, the expanded human environment acts as a testing ground to explore how design of public spaces affects the body-mind connection. Studies in environmental psychology have demonstrated that both the spatial and non-spatial aspects of urban spaces can significantly affect cognitive abilities, emotions and social interactions (Gifford, 2014). Consequently, public space becomes a key site for investigating how urban design impacts human wellbeing, within the framework of cognitive cities while offering insights into the complex relationship between physical space, human cognition, and social interactions.

3 Beauty and wellbeing: a new human-centered Renaissance

In the mid-14th century, was born in Italy the cultural and artistic movement of the "Renaissance" whose name derives from the verb "to be reborn", in fact it was said that the culture, which died with the barbarian invasions and the fall of the Roman Empire was finally ready, after a thousand years, to be reborn. This "cultural revolution" affected all philosophical and scientific disciplines but also the arts and architecture according to a vision based in Humanism, which was founded on a new vision of man.

In this context, urban development took on a new role linked to the centrality of man. In the same period the concept of the "ideal city", a city conceived as the ideal environment for man's life, was rising. The ideal city is planned through extremely rational and orderly solutions capable of guaranteeing the functional needs of daily living. This new approach on urban planning introduced itself as an utopian concept for the time, which is why many of these projects remained on paper or were partially realized.

The "ideal city" is spacious, harmonious and strictly based on geometry. This sort of obsession towards creating a perfect space is underlined by the almost total absence of man, as seen in the "View of an ideal city" attributed to Francesco di Giorgio Martini (1478–1501).

In the following centuries, the architecture of the city evolved through a succession of experiments whose aim was to showcase the capabilities of man and its wonders. Wonder and beauty have remained for centuries the objectives to be achieved to ensure that architecture, both on an urban and building scale, can be a source of pleasure for man: beauty is therefore a value linked to aesthetics. But what is the true value of the beauty of a place? How can it be measured? How does beauty connect to the human experience?

Today we are aware of the difficulty of talking about beauty in an absolute way, also aware of the fact that, over time, the sensitivity and taste of users can vary considerably and it is perhaps more correct to talk about happiness, a state of wellbeing that place, or that architecture could arouse (de Fromen, 2006). As Finnish architect, Pallasmaa (2005) noted almost a quarter of a century ago in his influential work *The eyes of the skin*: Architects and the senses, that architects have traditionally been so different in this regard, designing primarily for the eye of the beholder (Bille and Seimann, 2018; Pallasmaa, 2005; Pallasmaa, 2011; Rybczyński, 2001; Williams, 1980).

In recent decades, though, architects and designers have increasingly started to investigate the role of human senses in architectural design practice and the importance to consider all senses as sound, touch, smell, and on rare occasions, even taste (Spence, 2020). In this realm, beauty becomes something that gives satisfaction to all the senses, which is not limited to pleasing the physical sphere, but also invades our soul.

Man returns to the center of attention again in what we can define as a "New human-centered Renaissance" where the focus is no longer on his ability to know how but to acknowledge his necessity. All this leads to a paradigm shift from "humans that shape space" to "space shaping humans." The word "beauty", a word out of and for many anti-modern terms, is nowadays full of nuances (Mallgrave, 2010).

This new sensitivity is certainly the result of progress in the multidisciplinary approach that combines architecture, urban planning, neuroscience, cognitive studies and behavioral sciences, but also poses the awareness on how we can design cities that guarantee wellbeing and happiness of its inhabitants. The role of the theory of the extended mind introduced by Andy Clark and David Chalmers in the late 1990s is a central point of this framework that proposes a sort of externalism: an active externalism, based on the active role of the environment in driving cognitive processes (Clark and Chalmers, 1998). This perspective suggests that the human brain constantly generates predictions about the surrounding world to guide our behavior and perceptions on what we feel is not just what we see but also what we perceive. As highlighted by Thomas

Haetherwick in 2025: "The time has come to put human emotion back at the heart of the design process".

4 Human centered approach: Body + senses + emotions

Architecture is not solely composed of physical elements within a space, such as walls, doors, windows, fixtures, and floors. Rather, architecture encompasses a broader dimension of human existence. When we find ourselves within an architectural space, whether indoors or outdoors, we perceive and experience the surrounding environment through our senses.

As Mallgrave (2010) states, "our body and its emotional foundations, both on a conscious and preconscious level, shape the way we think or actively engage with the world, and in urban cultures, this shaping generally occurs within an architect-designed environment." This perspective underscores that the mind-body system is not a dualistic structure comprising two separate entities with distinct characteristics and properties. Instead, it is a unified system where the designed external environment influences how we react to the world around us.

Martin Heidegger, in *Being and Time*, distances himself from the dualistic view of mind and body by introducing the term *Da-sein*, which can be translated as "being-in-the-world" (Heidegger, 2006). In this concept, Heidegger emphasizes the importance of human relationships with the world in shaping individual identities.

If the surrounding environment affects our ways of thinking and emotional responses, it is crucial to understand how emotions function. Understanding the impact of space on our emotions is complex, as emotions are a combination of biological, cognitive, and social factors, shaped by cultural and societal constructs in which they manifest.

Human needs have always defined what we imagine, design, and build. However, architectural design has often lost focus on these needs, moving away from an empathetic model and succumbing to an ego-centric tradition, privileging vision over other senses (Pallasmaa, 2005). Designing a public space demands thoughtful attention. In the act of projecting an idea into space, it is essential to consider not only practical functions but also the multitude of people who will inhabit that space.

As Mallgrave (2018) notes, "Empathy is a talent that can be developed and refined, and it is more important than technical skills in the architect's practice". Therefore, when creating new segments of a city, new social spaces, or revitalizing urban fabric, the architect must use empathy as a key competence for ensuring the wellbeing of citizens.

Churchill (1943), "We shape our buildings, and thereafter they shape us", encapsulates the essence of the human-centered approach in architecture. This approach seeks to re-center the human experience in a manner akin to a new Renaissance. It focuses on designing spaces that cater to human needs, preferences, and experiences within architectural environments. By repositioning these elements, architectural design aims to create spaces that promote happiness, beauty, and wellbeing, thereby humanizing public spaces.

The relationship between body and environment is structured and profound, but the emergence of new sciences, such as

neuroscience and psychology, has reopened fields of inquiry and provided avenues for reciprocal exchange. This exchange is possible because, as embodied biological beings, we respond unconsciously to the characteristics of the surrounding environment. Our presence in the real world interacts with the spaces we inhabit—be they natural or designed environments, ranging from buildings to open spaces. This relationship between space and cognition is in a state of co-evolution, characterized by a cause-and-effect dynamic (Gallagher, 2017; Varela et al., 1997). This implies that the way architects design can influence and alter human behavior and neurophysiological responses.

Ultimately, the design of the spaces should be conceived as more than just the physical elements of the environment; it should embrace a broader human dimension, reflecting how our bodies, senses, and emotions interact within the built environment (Hastlerwick, 2021).

5 The extended public space: taxonomy and case studies

If we look at the contemporary city, public space has undergone a degree of innovation with few equals in other typologies. This development goes hand in hand with the emerging complexities of our society at large, and over the past decades, public space in itself has been a testing ground able to respond and adapt to these evolving societal conditions.

Within this framework, this paper sets up a taxonomy of six types of public spaces selected as paradigms of different approaches to the design of the public environment, each of which has innovated in a specific aspect (ritual-based, body-based, sensory-based, atmosphere-based, performance-based, and intelligent/augmented-based) capable of maximizing the experience of the space while guaranteeing the user's wellbeing through different strategies (Figure 1).

The taxonomy is constructed from the acknowledgment of specific "prompts" or "triggers" given in each space as a foregrounded characteristic that promotes urbanity. These "prompts" promote perceptual, cognitive and behavioral responses to improve the human experience. For instance, in ritual-based public spaces, the socio-cultural practices are the main foregrounded elements that promote the generation of urbanity; on the opposite side, in intelligent/augmented-based public spaces, the integration of advanced technologies to enhance user experiences in real-time is the main foregrounded characteristic. The range within the taxonomy, from ritual-based to intelligent/augmented-based public spaces, has been deployed to cover an array of intermediate conditions based on different "prompts" or "triggers" that facilitate the emergence of the human experience.

This research employs a qualitative methodology to examine pioneering and emblematic urban project realized in the last 20 years by key figures of contemporary architecture who **put back in the game** the rules of the project by placing at the center human experience of the space. These are not just architects or designers but above all persons with an avant-garde vision capable of writing the history of public space in the 21st century. The selection of case studies was guided by their adherence to any of the definition of public space as outlined in the Charter of Public Space (Gutiérrez et al.,

2016): "Public spaces are a key element of individual and social wellbeing, the places of a community's collective life, expressions of the diversity of their common, natural and cultural richness and a foundation of their identity, as expressed by the European Landscape Convention. The community recognizes itself in its public places and pursues the improvement of their spatial quality." The taxonomy of the new public spaces was constructed to highlight distinct approaches in rethinking design elements (e.g., light, color, spatial organization, and materials) in response to evolving societal needs. These spaces were chosen for their innovative strategies in addressing user experience and wellbeing while integrating elements that promote urbanity. This qualitative approach allows for a nuanced understanding of how different public spaces designs contribute to the extended mind concept, integrating cognitive, sensory, and emotional dimensions into the built environment. While the study does not rely on quantitative data, it draws on critical analysis of urban contemporary projects recognized for their forward thinking and innovative approaches to public space design.

5.1 Ritual-based public space

Ritual public space represent a space whose use is strongly linked to the culture and tradition of the place it is connected to the values of personal and collective identity. History brings an example of spaces that owe their success to the ability to embrace social and cultural practices. One of most celebrated example is "Piazza del Campo" in Siena, Italy, beating heart during the days of the traditional "Palio delle Contrade" and spontaneous meeting place throughout the year and Jemaa el Fna square in Marrakech, Morocco, where the social life of the city takes place, both day and night. If on one hand the historic squares update their functions, on the other, the contemporary ones attempt to respond to the need to deal with a new way of experiencing sociality (Binda, 2020).

The social aspect, not only relating to urban regeneration but also to the construction of an idea shared with citizens, becomes fundamental for the success of the project.

The Superkilen Urban Park, built in 2012, by Superflex, BIG, and Topotek 1, and situated in Nørrebro, in the semi-suburban neighborhood of Copenhagen, Denmark, is certainly one of the most representative projects of this approach. The neighborhood presented a social fragility due to the numerous presence of immigrants of different nationalities, each of them linked to their own culture and traditions.

The project intends to represent a coexisting multicultural society that looks at the park as a social construct (Lukin, 2020). The urban park, which extends for 790 m, is no longer uniform but divided into three fundamental parts: the western one characterized by shades of red (with a concrete and impact-resistant vermillion flooring), the central one characterized by black and gray slark (also paved with asphalt and impact-resistant rubber alternating with white stone bands to create an artistic design), the third "more traditional" area is green and meadows.

Superkilen is a world exhibition of furniture and everyday objects from all over the world, where the local residents, from around sixty different countries, were asked to suggest objects they missed from their home countries, and which they thought could enhance the Danish urban space. Walking along the park feels like

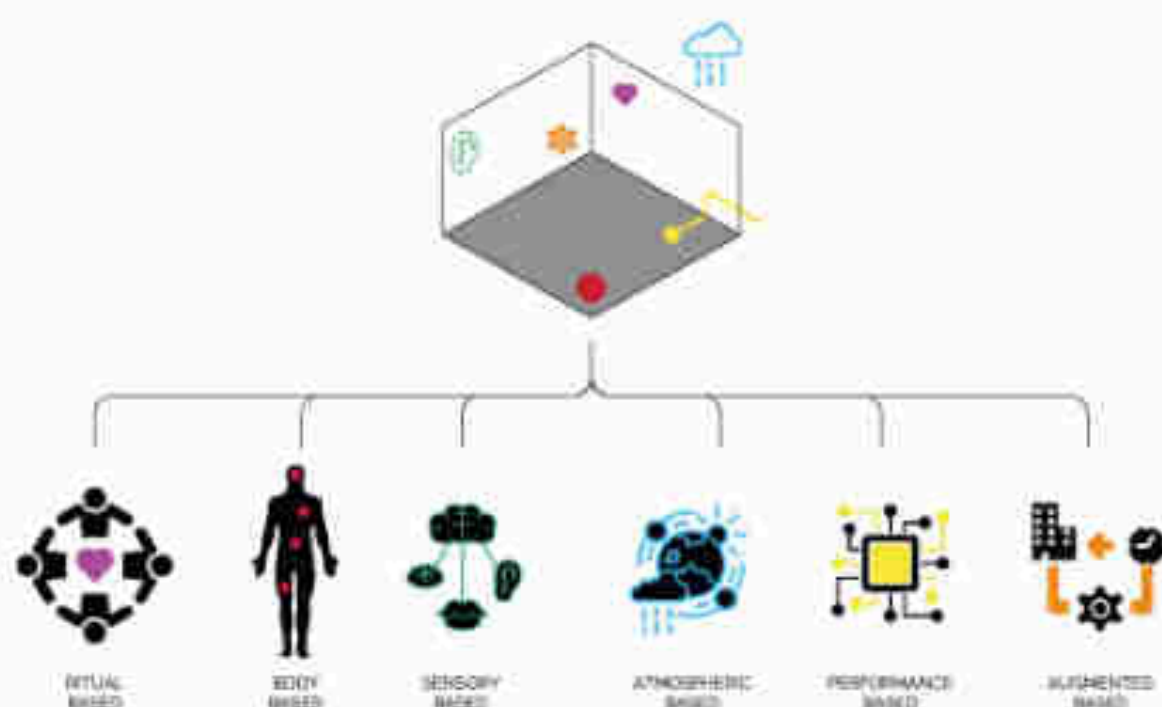


FIGURE 1
The taxonomy of the experienced public space.

travelling around the globe as you are confronted by neon signs from the U.S. and Russia, swings from Iraq, Stadium benches, a Spanish bull sculpture, a fountain from Morocco, a boxing ring from Thailand, English litter bins and even Palestinian soil. Social practices are certainly different from conventional ones.

Narrative is the result of a design process that takes into consideration the aspirations and needs of the users that shows how the contemporary public space is able to support new rituals and traditions just like the spaces of the past. The case study of Superkilen re-evaluates the importance of ritual practices in contemporary society and highlighted their versatility and ability to adapt (Lamm, 2014) (Figures 2, 3).

5.2 Body-based public space

Body-based public spaces represent an approach to design that considers how to maximize or orient the movement of the body affirming the centrality of corporeity in the experience of the space. It is an approach that aims to overcome the aestheticization of the urban landscape (Jacquez and Hertz, 2018; Jacquez and Frommhold, 2015). Proprioception, or the ability to recognize the position and movement of one's body in space without visual aid, inevitably influences our ability to navigate and comprehend architectural spaces. The proprioception is intrinsically linked to the concept of the architectural scale. Architects such as Le Corbusier explored this concept through the "Modulor", a system of proportions based on the measurements of the human body (Johnson et al., 2014). The degree of wellbeing perceived within a space is certainly linked to the ability to involve the movement of the body or guide it towards certain actions.

A tangible example is Governors Island Park project, "The Hills", released by West8 in 2010, where a new topography defines sloping landscapes based on 4 themed hills that rise as high as 30 feet above the island to offer a unique 360-degree panoramic experience of New York.

The involvement of the body has different intensity depending on the hill passing from a more or less active involvement of the body.

"Grass Hill" the lower hill, is characterized by a grassy slope perfect for naps and relaxation. "Slide Hill" can be considered as the playful hill where four slides carved into the landscape invite to play, therefore to put your body in movement. "Discovery Hill", the hill higher than the previous one, is instead characterized as the place of contemplation where the body can be relaxed and in touch with nature. "Outlook Hill" is the park's tallest hill where interaction with the sunset and body movement are encouraged by a pathway constructed out of reclaimed granite seawall blocks through which is possible to reach the top of the hill where you can enjoy the view of downtown Manhattan.

It is clear the mindful body approach that this park used to produce diverse movements and atmospheres and the ability of the designers to create spatial experiences that help us make experience of the environment (Figures 4, 5).

5.3 Sensory-based public space

Designing with a Sensory-Based approach includes the potential for a new design paradigm centered around perception and the triggering of the senses. Focusing on the five senses

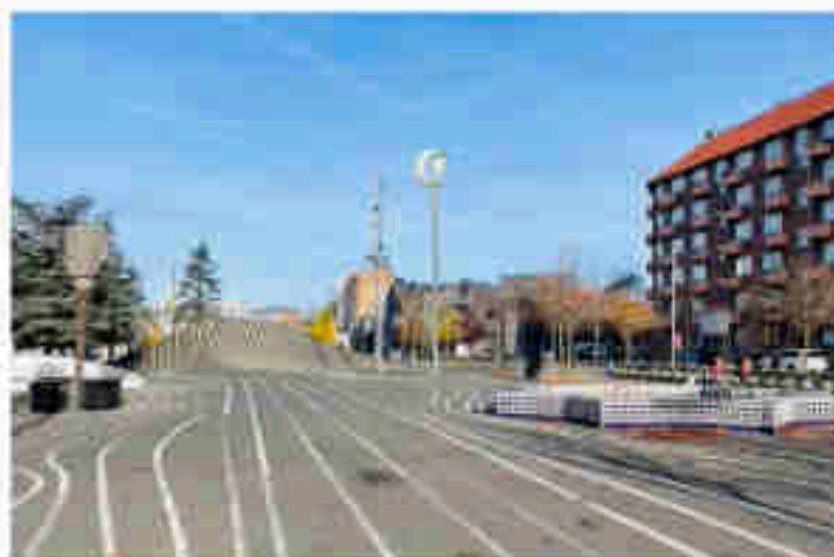


FIGURE 2
 View of the Superblock Block City with the project design on the ground. © Lorenzo Marini.



FIGURE 3
 View from the South Sea Net Zone with the vertical design elements. © Lorenzo Marini.

means creating a spatial experience with a heightened sensitivity capable of establishing new relationships between the body and the surrounding space, influenced by complex sensory processes that extend beyond mere vision.

When discussing New York City parks, Central Park often dominates the collective imagination. However, the Hudson River Park, with its vast expanse and stunning river views, is Manhattan's second-largest park. Within the sequence of piers along the river, the new project at the former PIER54, known as Little Island and designed by the Heatherwick Studio in

2021, emerges as a natural extension. This park, suspended over the water, offers a truly sensory experience that engages all the senses.

The integration of interactive sound installations and the constant presence of natural sounds produced by the Hudson River's waves continuously stimulate visitors' auditory experiences, offering moments of relaxation and active engagement. This is further enhanced by the large area designed for musical and non-musical events facing the river. Supporting this, the study by [Abrams et al. \(2019\)](#) demonstrated that natural sounds, such as flowing water,



FIGURE 4
The base slide of Slide #1. © Andrea De Cristis.



FIGURE 5
View from the top of the sculpture on Slide #1. © Andrea De Cristis.

can significantly reduce stress levels, contributing to the users' psychophysical wellbeing.

The tactile experience is supported by diverse pathways and materials, ranging from concrete to wood and stone. In certain areas of the park, it is almost possible to climb the artificial hills formed by the 132 concrete "vessels" rising from the river

(Farrimond et al., 2021). Sight is certainly one of the dominant senses at Little Island. Thanks to the breathtaking views of the Manhattan skyline, vibrant greenery, and the seasonal colors of blooming plants, the visual experience is constantly stimulated. The exposure to a natural landscape is further recreated through 240 different plant species (Farrimond et al., 2021), which have



FIGURE 6
View from the Little Island 22° avenue in Chicago.



FIGURE 7
A view of vegetation and a path of Little Island 22° Avenue in Chicago.

been shown to accelerate stress recovery and improve psychological wellbeing, as demonstrated in other natural environments (Kaplan and Kaplan, 1999; Ulrich, 1983) (Figure 6).

The olfactory experience also plays a fundamental and immersive role in navigating the project. The scent of plants and water is central, thanks to areas rich in flowers that emit natural fragrances, promoting relaxation, while the presence of the river adds an additional olfactory layer that can positively influence mood and reduce anxiety levels (Hart, 2009). Finally, although less prominent in the architectural experience, the sense of taste is introduced through the possibility of consuming products in the refreshment areas and the bar located in the main square (Figure 7).

5.4 Atmospheric-based public space

The Atmospheric-Based design approach introduces a new design paradigm centered around climate, weather, and atmospheric conditions. Paying attention to atmospheric elements means consciously designing spatial experiences, adapting to environmental changes, and creating new relationships between space and the climatic phenomena that influence it. This approach goes beyond mere visual perception and incorporates the sensory dimension of climate, such as heat, wind, humidity, and light, to generate spaces capable of dynamically interacting with the natural environment and its complex atmospheric processes.

In the city of Hamar, in Southern Norway, winters are cold and harsh, with temperatures dropping as low as -20°C , while summers are warm and dry, reaching up to 25°C . The redevelopment process of Svingtorg Square, carried out by the Ecosistema Urbano studio in 2011, was a pioneering participatory initiative that involved active engagement from the local community. The project employs a genuine seasonal strategy that ensures the usability of the space throughout the year and under varying weather conditions.

The planting of deciduous trees, combined with overhead structures, increases shaded areas during the summer, while pavilions are opened to enhance air circulation. Additionally, the circular ring of the square transforms into a fountain, with water jets that help cool the environment. In winter, the deciduous trees lose their leaves, allowing light to penetrate on cold but sunny days. Underneath the pavement, a snow melting system ensures the surface remains free from snow, keeping the square accessible, while the circular ring converts into an ice-dating rink. The initial project also included the installation of weatherproof umbrellas (not implemented), which would increase shaded areas and provide misting in the summer, while radiating heat during the winter months (Figures 8, 9).

5.5 Performance-based public space

Performance-based public spaces represent an approach to design that links performance-based technologies and energy



Figure 6. Participants (families and school children) at the main square of Havana. © González-Gómez



Figure 7. Top-down view of Havana. © González-Gómez

systems linked with the deployment of materials, lighting, and responsive surfaces that enable spaces that can dynamically adapt to environmental, climatic, and social conditions. At the core of performance-based design is the integration of performance-based technology that might use advanced sensors, data-driven systems, and Internet of Things (IoT) networks that allow public spaces to respond to real-time changes in their environment. This approach might be used for design and monitoring to enable automatic adjustments to systems to improve, for instance, comfort and reduce energy consumption (Figures 10, 11).

In Seonjlo 7,017 Skygarden, Seoul, South Korea designed by MVRDV in 2017, such technologies are embedded throughout

public spaces to continuously track environmental conditions and optimize the user experience. It is a prominent example of performance-based design in public spaces due to its dynamic integration of technology, environmental responsiveness, and social adaptability.

Designed as a green infrastructure, it improves the environmental conditions of the surrounding urban area. By planting over 24,000 trees and plants that are indigenous to South Korea, the Skygarden acts as a green lung within the city, contributing to air purification and mitigating the urban heat island effect. The pathway features smart LED lighting that adjusts based on pedestrian traffic and the time of day, enhancing energy



FIGURE 10
Scapeplan project made by MVRDV, Creative Commons.



FIGURE 11
Scapeplan project made by MVRDV, Creative Commons.

efficiency and user experience. By incorporating a dynamic lighting system, the space ensures safety and creates an inviting atmosphere, while minimizing energy consumption through sensors and automated adjustments. In addition, Digital kiosks provide real-time information on environmental conditions.

The design also takes into account the need for passive cooling and ventilation, ensuring that climate comfort is maintained for pedestrians even during the hot summer months. The park functions as an urban promenade, offering diverse public amenities such as cafes, exhibition spaces, and seating areas, which can be reconfigured to host events or accommodate different social activities.

5.6 Intelligent/augmented-based public space

Intelligent and Augmented-Based public spaces integrate advanced technologies to enhance user experiences in real-time. They utilize AI protocols, sensors, and data-driven systems to generate adaptable and user-oriented spaces. The future urban development by MVRDV Innovation Park, located in Heidelberg, Germany, stands as a pioneering example of how advanced technologies can be integrated into public spaces to enhance user experiences. This innovative project, winner of a competition in 2023 and not yet built, showcases the transformative potential of



FIGURE 12
Innovation Park, digital landscape visualization. García, García, and García © 2025



FIGURE 13
Innovation Park, digital landscape visualization. García, García, and García © 2025

urban design when coupled with cutting-edge technologies, making it a prime example of technological or augmented-based public spaces (Figures 12, 13).

At the heart of the Innovation Park is its commitment to harnessing Artificial Intelligence and data-driven systems to create a dynamic and interactive environment. The park utilizes a sophisticated array of sensors and digital tools that gather real-time data on environmental conditions, foot traffic, and user interactions. This information is crucial for adapting the park's features to the needs and behaviors of its visitors. For instance, AI algorithms can analyze patterns in usage, allowing for responsive adjustments in lighting, climate control, and even landscaping, ensuring optimal comfort and engagement throughout the day.

In addition, the Innovation Park integrates immersive technologies. Augmented reality (AR) and virtual reality (VR) installations enable users to engage with the space with different types of interactions. Visitors can access digital overlays that provide additional layers of information about the park's design, historical context, or ecological significance. This immersive experience fosters a deeper connection between users and their environment, transforming passive visits into augmented experiences.

6 Discussion

The design of future public spaces must embrace varying levels of intervention through "pumps" and "triggers." These interventions

TABLE 1 | Design paradigms for public space: features, potential synergies, challenges, and limitations.

Design paradigm	Key features	Potential synergies	Challenges/Limitations
Ritual-Based	Socio-cultural practices, collective rituals	Enhances urban identity and social cohesion	Limited adaptability to diverse demographics
Body-Based	Physical activity, movement	Promotes health and well-being	Accessibility for users with mobility issues
Sensory-Based	Light, color, texture, material	Stimulates emotional and sensory engagement	May require costly materials or ongoing maintenance
Atmospheric-Based	Overall ambience, mood influence	Supports diverse user experiences	Subjective interpretation of ambience
Performance-Based	Interactions, activities, dynamic design	Activates urban spaces dynamically	Needs ongoing management and programming
Intelligent-Augmented-Based	Advanced technology, real-time engagement	Real-time adaptation, data-driven insights	Digital divide, potential for exclusionary practices

should not be viewed as isolated elements but as integral components of a cohesive framework, interconnected with broader urban networks. This paper categorizes specific qualities derived from each case study, providing a structured approach to analyzing and interpreting public spaces. However, the ultimate aim is not to compartmentalize these categories but to weave their diversity into a unified, human-centered vision for contemporary public spaces.

Achieving this integrative approach requires interdisciplinary collaboration, drawing on insights from architecture, urban planning, neuroscience, and psychology. Such cross-disciplinary dialogue is essential both upstream, during conceptualization and design, and downstream, through post-implementation evaluation and refinement. For example, tools like the Perceived Restorativeness Scale (Hartig et al., 1996; Kaplan and Kaplan, 1989) and neurophysiological metrics (e.g., alpha brainwave activity or heart rate variability) can evaluate the impact of public spaces on behavioral and physiological responses. These measures offer tangible evidence of a space's effectiveness in enhancing the human experience.

The interplay between disciplines ensures that the design of public spaces goes beyond aesthetic or functional considerations, addressing cognitive, sensory, and emotional dimensions. For example, neuroscience can reveal how spatial configurations affect neural activity related to stress reduction or attention restoration, while environmental psychology can identify how specific design elements foster a sense of belonging or community.

To summarize the six design paradigms introduced, this study suggests the following framework:

- **Ritual-based spaces:** Rooted in socio-cultural practices that foster a collective sense of belonging and urbanity.
- **Body-based spaces:** Prioritizing physical movement and embodiment to enhance wellbeing.
- **Sensory-based spaces:** Engaging sensory perception through light, color, and materials to elicit emotional responses.
- **Atmospheric-based spaces:** Shaping the overall ambience to influence mood and social behavior.
- **Performance-based spaces:** Encouraging dynamic interactions and activities to activate urban life.

- **Intelligent/augmented-based spaces:** Leveraging advanced technologies to create adaptive and real-time user experiences.

These paradigms are not mutually exclusive but can work synergistically. However, potential challenges, such as the digital divide or limited accessibility, must be addressed to ensure equitable outcomes for diverse population groups.

Table 1 provides a comparative summary of these approaches, outlining their key features, synergies, and potential limitations.

This interdisciplinary and synergistic approach provides a roadmap for designing public spaces that not only meet functional and aesthetic needs but also resonate with the cognitive and emotional dimensions of human experience, ultimately contributing to the creation of spaces that are inclusive, adaptable, and restorative.

Finally, this study, through the collection and discussion of these six new paradigms, seeks to offer a typological upgrade to the definitions already established by the Charter of Public Space. The aim is to propose the creation of new urban spaces that transcend mere formal design, instead focusing on experiential qualities capable of fostering wellbeing and positively influencing human behavior within an extended mind vision.

7 Conclusion

In conclusion, this paper emphasizes the critical importance of rethinking how we design public spaces taking into account an 'extended mind' that encompasses the relationship between body, mind, and resulting experience in the built environment. Drawing on a multidisciplinary approach, through the exploration of six prototypical public spaces as design paradigms, the paper suggests that public spaces must evolve into laboratories that test these emerging relationships. The shift towards a cognitive city paradigm requires a design approach that places human experiences at its core, advocating for urban environments that are humanized to continuously enhance urban life's emotional and sensory dimensions.

This paper lays the ground for future work. In particular, the intent is not merely to provide the public space taxonomy

but to open up new avenues for scientific and interdisciplinary studies, particularly those that bridge the fields of neuroscience and environmental psychology, which have increasingly been recognized as critical to understanding human behavior in urban environments (Eberhard, 2009; Eberhard, 2025).

Next phase will focus on robust cross-disciplinary collaborations that can assess how specific parameters influence psychological and physiological responses (Giamberini, 2016), both at the quantitative and qualitative level through the implementation of specific metrics and data collection deployed on site.

By setting the stage for further investigation, this paper underscores the importance of a holistic approach to urban design—one that merges the rigor of “scientific inquiry” with the “explorations of architectural practice” to improve the overall human experience in cities (Montgomery, 2013). The ultimate goal is to create a methodological foundation for future studies that will refine the integration of neuroscience and environmental psychology into urban planning, with the potential to reshape urban design theories through a human-centered approach.

Thus, this research does not merely stop at the definition of a foundational taxonomy and case studies, but rather acts as a catalyst for ongoing scientific-oriented explorations into the cognitive city paradigm, where public spaces are designed with a deeper understanding of the interaction between the human brain, body, and environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

References

- Allam, Z., and Newman, P. (2018). Redefining the smart city: culture, mobilizing, and governance. *Smart Cities* 1, 11. doi:10.3389/fsmart.2018.00012
- Alvarado, J. J., Whinn, S., and Nelson, M. E. (2010). From recovery dating exposure to urban sound and environmental noise. *Int. J. Environ. Res. Public Health* 7, 131, 1049–1046. doi:10.3390/ijerph7071046
- Baby, M. (2016). *Interting future cities*. MIT Press.
- Balla, M., and Santamaría, T. E. (2018). “Interspecific relationships: domains, processes and practices” in *Japan and western: Global and primary issues*. Editors D. Brown (London, United Kingdom: Routledge), 4, 137–154.
- Carmori, M. (2010). *Public places, urban spaces: the dimensions of urban design*. 2nd Edn. Oxfordshire, United Kingdom: Routledge.
- Chakrabarti, S. (2010). *The urbanism of authority*. Princeton University Press.
- Churchill, W. (1942). *Speech at the house of lords*. London, United Kingdom: Hansard and Winston Churchill.
- Clark, A., and Chubb, D. (2006). The extended mind. *Analysis* 66, 7, 7–19.
- Cohen, P., Jenkins, D., and Vitaro, F. (2014). The impact of an urban park on air pollution and noise levels in the Mediterranean City of St. Rem, Italy. *Environ. Pollut.* 183, 73–85.
- De Botton, A. (2006). *Architecture's ethics*. Farnham, UK: Ashgate.
- Dal Sogno, M., and Bielek, G. (2010). *Urban machine: public space in a digital culture*. MIT Press.
- Eberhard, L. P. (2009). *Being Analogous: the experience of neuroscience and architecture*. Oxford University Press.
- Ellul, C. (2015). *Places of the heart: the phenomenology of everyday life*. Belknap Library Press.
- Emmons, D., Ju, E. W., McMillan, C., Parnell, H., Sobsey, L., and Whit, J. (2013). *A new kind of New York*. *Arch. J.* 2, 4–13.
- Galagher, S. (2017). *Emotion neuroscience*. Oxford University Press.
- Giamberini, E., Fiamingo, E., and Sisti, M. (2015). *The culture of public space*. Torino, Italy: Edizioni International 129.
- Gold, J. (2011). *145: between buildings: using public space*. Washington, DC, United States: Island Press.

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Conflict of Interest

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- Gifford, R. (2014). *Environmental psychology: principles and processes*. OpenStax Books.
- Heilig, T., Korpela, K., and Evans, G. (1998). Validation of a measure of perceived environmental restoration. *Psychol. Rep.* 20, 1002305223.
- Hetherwick, T. (2010). *Homeless: a mother's quest in building our world*. US: Penguin Books.
- Hickigley, M. (2006). *Evans & Tunstall*. Malden: Malden, N. H.
- Holt, R. J. (2005). Aromatherapy facts and fiction: a scientific analysis of efficacy effects on mood, physiology, and behavior. *Int. J. Aromat.* 119 (2), 263–290. doi:10.1080/020417005002235011.
- Jacob, A. A. (2022). Influence of urban street vending on pedestrian experience and behavior: a systematic quantitative review. *J. Comput. Urban. AG* 7 (1), 138–143. doi:10.29044/comp2022.138-143.
- Jacques, P. R., and Bello, F. D. (Eds.). (2010). *History, Narratives, Memory: methodological Experiences*. Collection for the Understanding of the Contemporary City Volume. EDUEBA.
- Jacques, P. R., and Demerouti, W. (Eds.). (2022). *Experiencia metodológica para comprender la complejidad de la vida contemporánea. Experiencia Apreensiva Contemporánea*. Valencia: EDUEBA.
- Kaplan, R., and Kaplan, S. (1989). *The experience of nature: a psychological perspective*. Cambridge, UK: Cambridge University Press.
- Lalonde, B. (1981). *The production of space*. Wiley.
- Lanotti, D. F. (2014). *L'ospite pubblico come spazio vivibile. L'abitante dello spazio collettivo ed i progetti degli ultimi anni*. Babiluschi & Associati.
- Lidz, D. E. (2010). Chinese aesthetics and the Culture of Republic. *Studies in History and Theory of Architecture* 9, 228–244.
- Lyons, K. (1990). *The image of the city*. MIT Press.
- Malpasso, H. F. (2010). "L'ospite degli spazi" in *architettura e paesaggio*. Milano: Raffaello Cortina Editore.
- Malpasso, H. F. (2011). "From object to experience: The new culture of architectural design" in *H. F. (2010) in A philosophical enquiry into the origin of our ideas of the sublime and beautiful* (London: R. and J. Dutton).
- Richard, D. (1991). The end of public space? People's Park, definition of the public, and democracy. *Am. Assoc. Am. Geogr.* 85 (1), 104–130.
- Montgomery, C. (2012). *Happy City: how planning our lives through urban design*. New York: United States: Farrar, Straus and Giroux.
- Pollman, J. (2011). Architecture and the emotional sense: space, body, and the senses. in *Art and the senses* (Eds. F. Bacci, and P. Stokken) (Oxford: Oxford University Press), 594–598.
- Pollman, J. (2005). *The end of the 4th architecture and the senses*. Clarendon: England: Wiley.
- Rude, A. (2020). "Holding the line": Investigating how urban school leaders respond to gentrification in New York City schools. *Urban Education* 55 (12), 2115–2142.
- Rybicki, W. (2001). *The work of architecture*. New York: The New York Public Library.
- Spence, C. (2020). Multisensory Flavors: Perception, Thinking, Mating, Power, and Eating within and between the Senses. *Psych. Sci.* 31 (4), 407. doi:10.1177/095679762094407.
- Ulrich, E. (1990). "Aesthetic and affective response to natural environment," in *Behavior and the natural environment*. Editors L. Altman, and J. Wohlford (New York, NY, USA: Springer).
- Yonke, J. T., Overgreen, J., and Roud, E. (1991). *The embodied mind: cognitive science and human experience*. MIT Press.
- William, A. B. (1980). *The urban edge: A reflection of architecture and urban design*. San Francisco: Francisco Center for Architecture and Urban Studies.

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Spatio-artistic thresholds foster human-nature connections for sustainable transitions: cases of vernacular facades in Bhal, India

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Introduction: Despite growing awareness of the society-nature division as a root cause of current socio-ecological crises, sustainability transition approaches often overlook architectural design's role in fostering human-nature connections (HNCs). In fact, much of sustainable architecture practices also prioritise designing for technical efficiency and mitigation over designing for 'relationality' and nurturing HNCs. This gap highlights the need to redefine architecture as a system shaping and transforming human interactions with the world, and to develop relational design approaches for achieving sustainable urban transitions.

Aim: This paper introduces vernacular architecture as an exemplar of relational design. It aims to assess the vernacular Indian dwellings for 'relationality,' targeting their spatio-artistic entrance facades to identify HNCs fostered by these architectural thresholds.

Method: To achieve this, the visual ethnography method was utilised by triangulating photographs and sketches with observations for a case study of two wooden vernacular facades in Bhal, India, as representative examples of a typical half-timber Indian dwelling. Four areas of artefact analysis, supported by grounded theory techniques, were employed for the interpretive analysis of the facades to uncover embedded dimensions of HNCs.

Result: The findings indicate eight thematic levels of HNCs fostered by the intricate interplay of spatial-artistic features in facades, which together create a profound aesthetic experience of nature in the everyday life of inhabitants and also correlate to existing biophilic patterns. These elements serve functional purposes, along with expressing ecological consciousness and imparting cultural meanings to promote multiple internal-external connections with nature.

Discussion: Additionally, a potential analytical framework to evaluate architectural facade design is proposed along with the guidelines for relational design of these spaces. The results suggest that designing spatio-artistic facades and thresholds in architecture can act as a leverage point to facilitate relational ontological shifts towards nature in the human psyche for sustainability transitions. These insights are essential for socio-ecological urban planning and design to reorient societies with nature.

KEYWORDS

relationality, architecture, vernacular facades, human-nature connection, sustainability transition

1 Introduction

Overcoming dichotomies between society–nature and human–nonhuman embedded within current development trajectories of modern industrial societies is considered crucial for transformational change to sustainability (Lee et al., 2008; Van et al., 2009). Socio-ecological transition scholars argue that sustainability must be rethought in relational and experiential terms and not just through systemic modelling or carbon accounting (Gooden et al., 2014; Lockin et al., 2010). Relationality as a principle is defined as a fundamental shift from modern dualistic thinking towards an understanding of the radical interdependence of all things, human and nonhuman (Lalabai et al., 2011). This has led to an increase in research aimed at identifying alternative relational approaches and engaging with paradigms and systems associated with human–nature connections (HNCs) as ‘deep’ leverage points to address the sustainability crisis. Architecture, as a fundamental medium of our being in the world, can shape and transform human interactions with the world (Williams, 2014), yet it remains underexplored as a design for sustainability transitions. Sustainable architecture, in fact, also adapts reductive approaches to efficiency and mitigation rather than relational approaches to integrate buildings as part of socio-ecological systems and a network of relationships, including those between humans and nature. Thus, there is a relational shift deemed necessary within the architectural discipline to address current sustainability crises.

Vernacular architecture, defined as a communal built environment shaped by HNCs (Bachnik, 1994), can offer valuable insights for relational architectural design to achieve sustainable urban development. These structures represent what Alexander (1979) refers to as a timeless way of building, where each space is brought to life by specific patterns of relationships among the elements that are distinctive to its people, culture, and place. India, known for its diverse vernacular architectural styles, features thresholds (i.e., entrance verandas) as a common architectural characteristic of dwellings across its various regions, which is considered a unique socio-ecological design element (Jain, 2002; Tiwari and Sharma, 2016). These thresholds are ‘patterns’ (Alexander et al., 1977) born from centuries of lived experience, creating a language of relationships—between inside and outside, public and private, human and nonhuman, family and community. The design of these spaces physically connects the natural exterior with the human-occupied interior and is also symbolically adorned with distinctive art forms depicting local flora, fauna, and mythical motifs as part of their façade (Tajiri and Jall, 2012). It presents a unique system of spatio-artistic patterns, interdependent at many levels, that makes these structures alive and provides them with biophilic qualities.

Gooden (2016) emphasises that the responses and behaviours elicited by designed objects can realign human interactions with each other and with nature. In fact, the life that occurs in a building is not only considered to be confined in the space, but is shaped by the space and its patterns (Alexander, 1979). Despite this, the authors are unaware of any research that has attempted to investigate these vernacular entrance façades as a relational interface to understand their role in fostering HNCs. To address this gap, the research aims to assess the entrance façades of vernacular Indian dwellings for HNCs. The objective of this paper is to identify various types of HNCs fostered by the entrance façade in vernacular Indian dwellings, with a focus on determining features and patterns nurturing relationality in

everyday life. This objective will be addressed by answering the following research question (RQ):

RQ1: What types of HNCs are fostered by the spatial features of the entrance façade within vernacular dwellings?

RQ2: What types of HNCs are fostered by the artistic features of the entrance façade within vernacular dwellings?

It is hypothesised that the designs of vernacular entrance façades offer opportunities for both internal (philosophical or cognitive) and external (experiential or material) HNCs to emerge in everyday lives. In this study, HNCs are documented and analysed for wood-crafted entrance façades of two vernacular dwellings in the geological region of Bhad in Gujarat, India. Initially, the documentation of these façades is conducted using visual ethnography, followed by an analysis for HNCs utilising Shiller's (2021) four-stage artefact analysis method, which is supported by a grounded theory approach. The significance of this paper is primarily highlighted in two aspects. First, it suggests that vernacular architecture serves as a key example of designing ‘relationally’, which involves creating spaces that promote an awareness of the interconnectedness of humans with one another, the earth, and various nonhuman entities. Second, it puts vernacular architecture in context with sustainability transitions, biophilic design and HNCs and briefly proposes a potential analysis framework and guidelines for architectural thresholds as spaces for human–nature interaction.

Section 2 sets the background of the research via a literature review of relevant studies at the cross-section of sustainability transitions, HNCs and architecture. Section 3 elaborates on the methodology and cases under study, followed by Section 4, which provides a detailed analysis of the case. Section 5 articulates the resulting HNCs and provides a framework and guidelines for relational threshold design, followed by a conclusion that summarises the major takeaways from this research and its limitations.

2 Background

2.1 HNCs, architecture and sustainability transition

Nature, under modernity and industrialisation, is not something inherently ‘natural’, rather, it is seen as a resource for economic development and an object that can be commodified, dominated, and reconfigured to suit human needs (Lalabai, 1999). Modern industrial society, devoid of reverence for the natural world, fostered a culture of exploitation—cultivating, manipulating, polluting ecosystems, and even eradicating natural resources (Ongun, 2003). As Gandhi famously stated, ‘Nature can cater to man's need but cannot cater to man's greed’. This manipulation and domination of nature has resulted in unprecedented socio-ecological changes that are advancing ‘wicked problems’ and threatening the planet's stability and sustainability (Aitmann, 2021; Akhtar and Wink, 2019; Bhattacharya and Gannon Haggithorn, 2021; Bickmann et al., 2009). Current trajectories of human development necessitate radical transformations to ensure a sustainable future, as incremental adjustments are inadequate to tackle the scale and urgency of current global challenges (Chakrabarti and

Truett 2006). In response, the discursive concept of ‘sustainability transition’ emerged from the idea that social and environmental problems demand transformative change in existing systems to move sustainable modes of production and consumption (Folke et al. 2017; Baklanoff et al. 2017).

Researchers studying socio-ecological systems in sustainability transitions identify human-nature division and society’s disconnection from nature as one of the root causes of current social and environmental challenges (Gruniger et al. 2017; Folke et al. 2011; Brown et al. 2018). In fact, the sustainability crisis is argued to be a crisis of the modern system of thought that imposes a dichotomous worldview ontologically separating humans from nature and generating binaries between culture/nature and human/animal (Folke 2009). Thus, to make radical changes in current trajectories negatively impacting the planet, an ontological shift is proposed by recognizing systematic interdependencies between society and nature (Folke et al. 2021) and rethinking the relational qualities of HNCs (Gruniger 2021; Lachar 2019; Levy et al. 2017). Relational ontology emphasizes that human survival and thriving are interdependent, rather than individual, acknowledging the existence of multiple worlds (pluriversal), each relational. This has sparked a growing research interest in understanding HNCs and their essential qualities as well as identifying alternative relational approaches to challenge modern dualistic and hierarchical HNCs for sustainability transitions (Vandenberg 2021; Barry et al. 2021; Freperell and Torres 2021; Walsh et al. 2021; West et al. 2020; Joo et al. 2019). As a result, diverse relational discourses are emerging like *biophilic hypothesis* (Kallert and Wilmer 2011), *reconnecting to the biosphere* (Johke et al. 2011), *nature deficit disorder* (Loom 2008), *connectedness to nature scale* (Slayer and Franz 2018), *nature relatedness* (Gibson et al. 2009), *human-nature resonance* (Gruniger 2021) across disciplines, addressing visions of the system associated with HNCs as ‘deep’ leverage points for transformational change.

In this context, Lachar et al. (2021) argue for a relational ontological shift in the discipline of design, given its historical role as a practice linked to anthropocentrism. Considering the values and behaviors that design objects elicit in people, influencing one’s being in the world and vice versa, it also holds significance in the consolidation of relational ontology for sustainability transitions (Gruniger 2019). Designing in a relational manner involves understanding that humans are in an inextricable relationship with each other, the planet, and various nonhuman beings (Gruniger et al. 2020). Aligned with this and to address current crises, the architectural discipline is also undergoing a relational shift from sustainable to socio-ecological design approaches by reframing it as a material expression of human-nature relations (Gruniger et al. 2019; Lachar and Malague 2021). This shift is deemed necessary because sustainable architecture has mainly focused on reducing negative impacts by improving the efficiency of existing systems, without challenging the root-level unitarian view of nature and its resources (Gruniger et al. 2019). Currently, where sustainable design adopts reductive approaches, socio-ecological design adopts regenerative approaches, which entail understanding flows and relationships in a site to inform design responses for enhancing the regenerative potential of a place, its people, and nature (Ellis and Hobb 2022). Diverse relational design approaches like *biophilic design* (Folke 2009; Kallert et al. 2013), *regenerative design* (Chen et al. 2013; Gruniger de la Cruz 2021), *multispecies design* (Gruniger et al. 2021),

nature-based solutions (Joo 2021; Wilmer et al. 2021), etc., are thus emerging in architecture. Of all these approaches, biophilic design is an innovative approach that has evolved and gained increased traction for restoring the inherent HNCs in the design of the built environment, further discussed in Section 2.2.

2.2 Biophilic design, patterns and vernacular architecture

Biophilic design is an approach that recognizes the low environmental-impact objectives of sustainable architecture as insufficient and seeks the long-term sustainability of restoring and increasing people’s positive relationships to nature in the built world (Kallert et al. 2013). It is a set of design strategies that attempts to translate biophilia – the inherent human affinity to affiliate with natural systems and processes—into the design of the built environment. Existing research indicates that biophilic architecture and exposure to nature and natural habitats can improve humans’ overall well-being and health, their cognitive performance, while also cultivating environmental attitudes and pro-environmental behaviour (Liu and Chen 2011; Leno et al. 2009; Takano et al. 2014). Although biophilic design is considered an innovation today, ironically, it was the way buildings were designed for much of human history (Kallert et al. 2013). Vernacular architecture is a biophilic built form. It has evolved through trial and error, in integration with the natural environment, using local materials, themes, and patterns of nature for building artefacts, in connection to culture and heritage, utilizing indigenous construction techniques, while addressing both tangible and intangible needs of the community (Joo and Kim 2021; Swastika and Day 2021). In fact, one of Kallert et al. (2013) two key dimensions of biophilic design is place-based or vernacular, with its own set of elements and attributes that enable design to be rooted in local ecology, cultural traditions, and patterns of life. The search for a socio-ecological approach to planning and design has thus led to an increasing research interest in vernacular architectural spaces with regard to their design that leverages and complements local socio-ecological factors and patterns (Gruniger 2021; Gruniger and Malague 2021; Tyron and Lee 2013).

By being site-specific – adaptive to climate and environment, self-sufficient – in natural and knowledge resources, and cost-effective – in economic and social terms (Gruniger 2009; Pradyumn 2018), it adheres to a unique combination of natural flows/ patterns of relationships in a place. It is also influenced by various tangible and intangible factors such as religion, beliefs, customs, philosophies, habits, regulations, building processes and ornaments/symbols (Lachar and Wilmer 2021). According to Alexander (1979), the buildings of the past offer one timeless way of building in which the space is infused with quality of life through varied patterns of relationship in space, which in turn supports the patterns of events that occur therein. Thus, the life that occurs in a structure is not simply rooted in the space, but is made up of the space and its patterns themselves. Vernacular architecture research over the years has focused on its materials, styles of buildings, environmental sustainability, building performance, thermal comfort, energy efficiency, traditional construction techniques and socio-cultural identity (Bhadani et al. 2021; Datta and Kumar 2021; Jayaraman et al. 2020). However, although vernacular architecture is defined as a communal built

environment shaped by human-nature relations (Shukla, 1964), they have rarely been studied from a relational perspective, specifically for the HNCs it fosters through design. This research gap prevents the acquisition of traditional knowledge and insights that could inform the design of patterns of relationships in architecture within the socio-ecological context of sustainability transitions. This paper aims to address this gap.

Architecture is a manifestation of culture; it represents the psyche or collective mind of a society in a material form, expressing and communicating its ideas, values, and beliefs (Hindia, 2011). Culture, in turn, is considered to shape worldviews and is in itself shaped by worldviews, which include values about life, reality, and nature (Shukla, 2001; Shukla, 2014). From this perspective, the diverse vernacular architectural forms in India express the collective psyche of its cultures, reflecting and communicating the ‘cosmocentric’ worldview that is central to Indian societies. Cosmocentrism recognises the interconnectedness of humans, nature, and the divine, viewing human life as part of a broader cosmic framework and ensuring constant linkage, interaction and a repetitive association with nature and the natural elements around us. This traditional worldview perceives the microcosm (self) and macrocosm (universe) as composed of the same fundamental elements (earth, water, fire, air, ether), reflecting the inherent unity of all existence (Rana, 2019; Rana et al., 2024). It articulates the mutuality and interdependence of all existence, with humans as an inseparable part of nature and nature as the very source of the universe (Vasudeva and Vasudeva, 1995). As a result, the concept of self is relational (Shukla et al., 2014) in India, reflecting the metaphysical harmony and interconnectedness of humans with all entities in a universal cosmic network (Hindia, 2011). Thus, vernacular architecture in India as material culture holds the potential to communicate what Eschola (2018) calls traditional cosmologies and to represent the human psyche of ecological consciousness inherent to its traditional communities. Researching these spaces can provide alternative socio-ecological design perspectives for reorienting societies to nature. It can render useful guidelines to transform human existence—body, mind, and soul—towards a relational ontology for transition to sustainability-orienting design.

2.3 Facades, nature-culture interface and vernacular dwellings

India is home to diverse vernacular dwelling forms influenced by its cultural diversity, different microclimatic conditions, and the availability of building materials (Rana et al., 2023; Rana, 2019). Despite these differences, vernacular architecture across urban and rural regions of India shares many common characteristics, like courtyards, thick walls, narrow openings, sloping roofs, etc., that contribute to their socio-ecological design (Prasanna and Das, 2021). Threshold space, defined as a complex multifunctional spatial structures that create transitions between different zones, often marking entrances to an area (Bourgeois, 2016), is one such common feature of its vernacular spaces. Semi-open porches and entrance-terraces are essential elements of environmental responsiveness, socio-cultural integration, and material efficiency in vernacular dwellings across the country (Jain, 2002; Vasudeva and Nagaswami, 2020; Vasudeva and Vasudeva, 2013). Architecture, as a fundamental medium of our being

in the world, can shape and transform our human experience of reality by framing, structuring, articulating, linking, separating, uniting, enabling, and restricting our interactions with the world (Shukla, 2014). This viewpoint emphasises the significance of entrance terraces as a relational design element that acts as a threshold, connecting the outside world with the interior and linking nature with culture in vernacular dwellings. The spatial characteristics of these terraces thus can influence the types of HNCs that develop as people inhabit these spaces. Despite this potential, there is hardly any research that has attempted to investigate these entrance thresholds and their role in mediating external (experiential and material) HNCs from the perspective of sustainability transitions.

Along with architecture, art has always been an evolving medium of cultural expression for traditional communities, serving as a source of inspiration and creativity throughout history. It is also an integral part of vernacular dwellings in India, where each region's local arts and crafts—such as painting, mosaic work, tile work, etc.—contribute to its diversity in vernacular structures (Vijaya and Lakshmi, 2017). These art forms are typically found as embellishments on the walls and facades of entrance verandas/courtyards in dwellings and are used to decorate homes, symbolise nature, represent everyday life, and serve ritualistic purposes. Common themes in these art forms include local flora and fauna, mythological figures, deities, epic scenes, and depictions of nature. *Bhil* and *Gond* wall paintings in Madhya Pradesh, *Chitrav* paintings of the *Dowari* tribe in Karnataka (Rana, 2020), fresco and mural walls of *Shikharwati* havelis in Rajasthan (Singh, 2013; Yadav et al., 2021), and stonework in temples, forts, and palaces (Sharma, 2011) are a few examples of art on facades of traditional dwellings. These art forms, both in their concepts and practices, are also firmly anchored in the traditional holistic, integral vision of HNCs. Indian Art, in fact, is considered rooted within a ‘cosmocentric’ cultural worldview, with creativity in both sacred and secular art growing out of the in-exactness of its traditional relational perspectives (Chakrabarti, 1990; Singh, 1995; Vasudeva and Vasudeva, 1995). As a result, traditional artists perceived the self as an extension of nature and held the belief that artistic creation, much like natural growth, relies on the foundational five elements (Singh, 1995). This relationship influenced their creative processes, promoting wise resource utilisation and symbolic interpretations of nature as reflected in their artistic creation.

In this context, entrance facades, in addition to their function as transitional zones physically connecting the inside and outside, also assume a significant symbolic role as artistic thresholds influencing the types of relationalities between inhabitants and nature. The facade embellishments—often featuring richly ornamental walls, columns, beams, brackets, etc.—carry symbolic meanings, reflecting the community's identity and relationship with their environment (Vasudeva and Vasudeva, 2014). In the western villages of Gujarat, India, organically evolved wooden vernacular dwellings showcase the artistic talents of their inhabitants, reflecting their agricultural lifestyle and cultural worldviews within design. The art of wood carving facades originated here as a unique cultural entry, encompassing symbolically in itself history, culture, mythology, religion, social values, inherited traditions, and human interpretations and expressions of nature (Shukla, 2004). Though created by individual artists and shaped by the tangible and intangible cultural forces of the region, it is an artistic projection of society and its ‘cosmocentric’ worldview. As Winston Churchill once said, “First we shape our buildings, and then our buildings shape us.”

This wood-crafted vernacular facade carries symbolism that can significantly influence inhabitants' lives, their values, and the kinds of relationships they develop with nature through daily experiences of its intricate craftsmanship. Art, in fact, possesses significant potential to forge internal (emotional or philosophical) HNCs with its capacity to evoke visceral experiences and expand consciousness. Despite this potential in vernacular architecture studies, we often tend to overlook these small-scale architectural features and patterns, neglecting to investigate the role of these subtle art forms in socio-ecological design. Therefore, in this research, we document and analyse spatial and artistic features in the entrance facade of two vernacular dwellings constructed using half-timbering techniques in the region of Bhil, Gujarat, India.

3 Materials and methods

3.1 Research design

The genesis phase of this research employed a narrative review method to explore the interconnections between sustainability transitions, socio-ecological systems, and vernacular architecture. This method allows for the consolidation of various information pieces into a readable narrative format, enabling the presentation and interlinking of diverse topics and investigations (Joshi et al., 2017; Green et al., 2018). It facilitated the summarisation of existing knowledge on these topics, identified gaps, and provided a conceptual background (discussed in Section 2) justifying the need for this study. This process allowed for articulation of the goal of this research to identify different types of HNCs mediated by the entrance facades in vernacular dwellings and to investigate the role of spatial-artistic features and patterns in vernacular facades nurturing these HNCs in everyday life for sustainability transition.

To achieve this goal, the study utilises the visual ethnography method. This method encompasses a wide range of approaches, which include photo elicitation, photography, family photos, GIS, art making, etc. (Van Donge-Sabbe, 2018). In this research, we triangulate photographs and sketches with observations as a method (Figure 1). Traditional ethnography involves systematic recording, analysis, and written descriptions of socio-cultural aspects to understand people and their activities within their natural contexts. Visual ethnography captures how artefacts are used, displayed, and interacted with in everyday life. It goes beyond textual descriptions by allowing for the documentation of artefacts in use, thus providing empirical grounding for visual analysis.

For analysis, the methodology follows Müller's (2021) and Langer and Hirschmann's (2017) four areas of artefact analysis outlined for material culture studies, taking an interpretivist paradigm, with authors as the primary research instrument. Several categorical variables, as shown in Table 1, are examined in the artefact under study to uncover patterns of spatial, symbolic, and relational dimensions. These categories served as descriptive anchors for understanding the design characteristics in the vernacular facades. This interpretive analysis of thresholds is further supported by grounded theory techniques, as suggested by Langer (2006) (cited in Müller, 2021), for the identification of HNCs.

This study follows a case study approach, employing the discussed research methods for gathering and analysing data to understand the HNC phenomenon within the entrance facade of vernacular



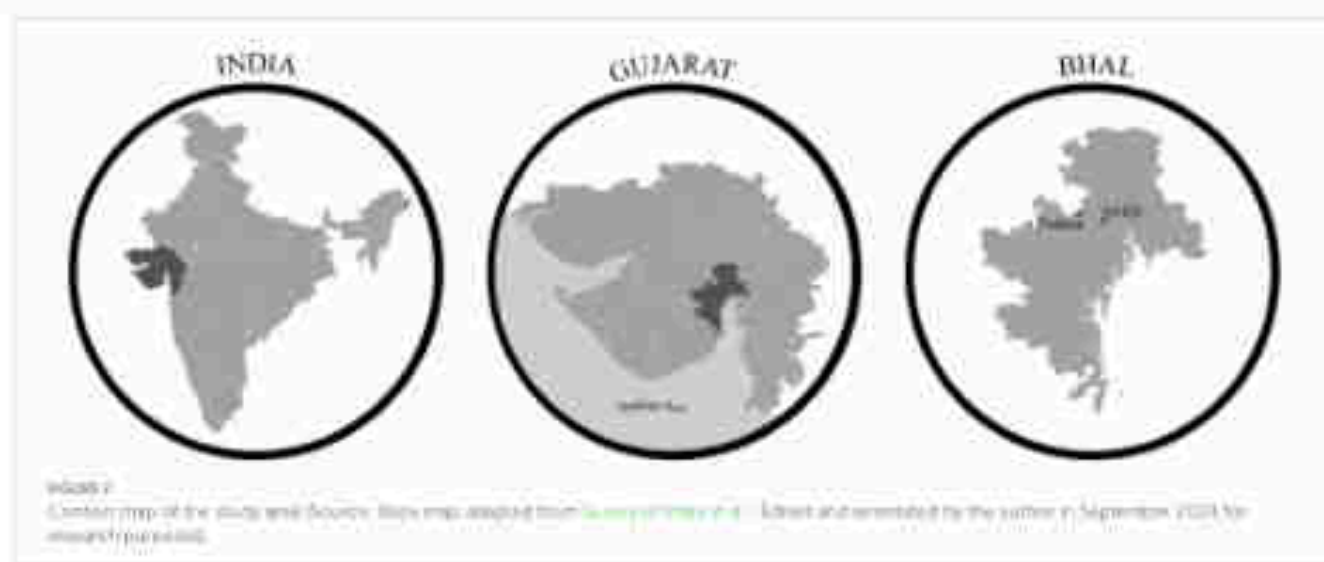
dwellings. Case study has a well-established history in architectural research, as it allows for effective analyses of phenomena within its real-life context using multiple sources of information such as documentation, observations, archival records and artefacts (Langer et al., 2005; Van, 2011). Thus, two vernacular dwellings in the geological region of Bhil, Gujarat, India, were selected as cases purposefully. To ensure relevance and rigour, four primary criteria were applied in identifying these vernacular dwellings: (a) the case should exemplify the typical characteristics of the half-timber vernacular architectural tradition of the country; (b) the typology of dwelling should be among those rapidly disappearing due to the homogenising effects of globalisation and contemporary development; (c) the case should have largely retained its original architectural configuration, or at minimums, provide sufficient visual evidence of its original form; (d) the case should belong to the region of the country which is less known and less studied for its vernacular architecture.

3.2 Site and case descriptions

Bhil is an ecologically complex semi-arid coastal region that spans approximately 100 km in length and 25 km in breadth on the left border of the Gulf of Khambhat (Cambay) (Van and Joshi, 2011) (shown in Figure 2). It is believed to have emerged due to the shifting

TABLE 1 Four areas of artifact analysis

Artifact analysis areas		Categorical variables to analyze
Conditions for existence	In which context(s) the artifact occurred and what is the history behind it? Examining why this artifact exists in the current context, as well as the cultural, ecological and social contexts that informed it.	Historical context Climate/ecological rationality Socio-cultural factors Ecosystems influence
Descriptive analysis	What is the artifact made of? What different elements does it consist? The systematic description of the individual elements which constitute the artifact.	Materiality Architectural elements Visual composition Construction techniques
Analysis of embedded meanings	What are the concepts and meanings to which the artifact is associated? Is it related both emotional or sensory qualities? Placing the external elements in an everyday context and considering the artifact in its entirety.	Semiotic meanings Formal ornamentation Linked (multi)everyday practices Narrative interpretations
Historical contextual analysis	In what context was the artifact produced? How is it produced? How and to what extent is it used and changed? The structure of meaning which ultimately form the basis for appearance of the artifact in its form.	Systems of production Knowledge transmission Evolution of use or form Continuity or discontinuity

Source: Adapted from [Muller \(2020, p. 44\)](#)

of the sea, resulting in a geographical landscape equally flat to the level of the sea, characterised by saline soil and water conditions, receiving an average annual rainfall of about 650 to 700 mm ([Cobb and Patel, 1960; Vyas and Joshi, 2011](#)). In the local dialect of Gujarati, Bhach means 'bechead'. This metaphor stems from the fact that, just as no hails grow on the bechead, nothing grows in this region, and one village appears to be floating in the mirage of another. Thus, timber is not naturally available in the region. Despite this, it has been widely used as a material for the construction of traditional temples to vernacular dwellings in this region. A typical dwelling, in fact, in most traditional Indian towns and villages was timber-framed, with brick infill and lime stucco on both sides (also known as half-timber structures) ([Taqi and Kati, 2011](#)). The emergence of traditional wooden architecture can be traced back to historical accounts of the communities living in Bhach. These accounts suggest that maritime trade and voyages were thrived in the area, with shipping routes extending from the Gulf of Khambhat to Diu and even reaching as far as Burma ([Shah and Patel, 1968](#)).

As a result, the evolution of half-timber structures in Bhach was made possible because the wood was imported in large quantities through sea trade, making it a locally available material in the region.

The region's unique geological and geographical features, along with limited resource availability, led to the development of an agricultural society characterised by a distinct productive philosophy, socio-cultural practices, and ecological awareness. These factors shaped a peculiar approach to dwelling construction in Bhach, where each dwelling was designed as a self-contained unit featuring an individual open front yard enclosed by a wall on all sides and accessed through a single doorway known locally as 'Dehi'. The main multi-storied building in this larger unit was constructed using a wooden framing system, with small bricks infilled within the frame. These bricks were set in place using mud mortar and finished with lime or mud plaster. The enclosed unit also included a separate sub-built cattle shed and often featured a *Tuber* (floral) plant, which may be found in a flower bed or in the open compound. The standout feature of this

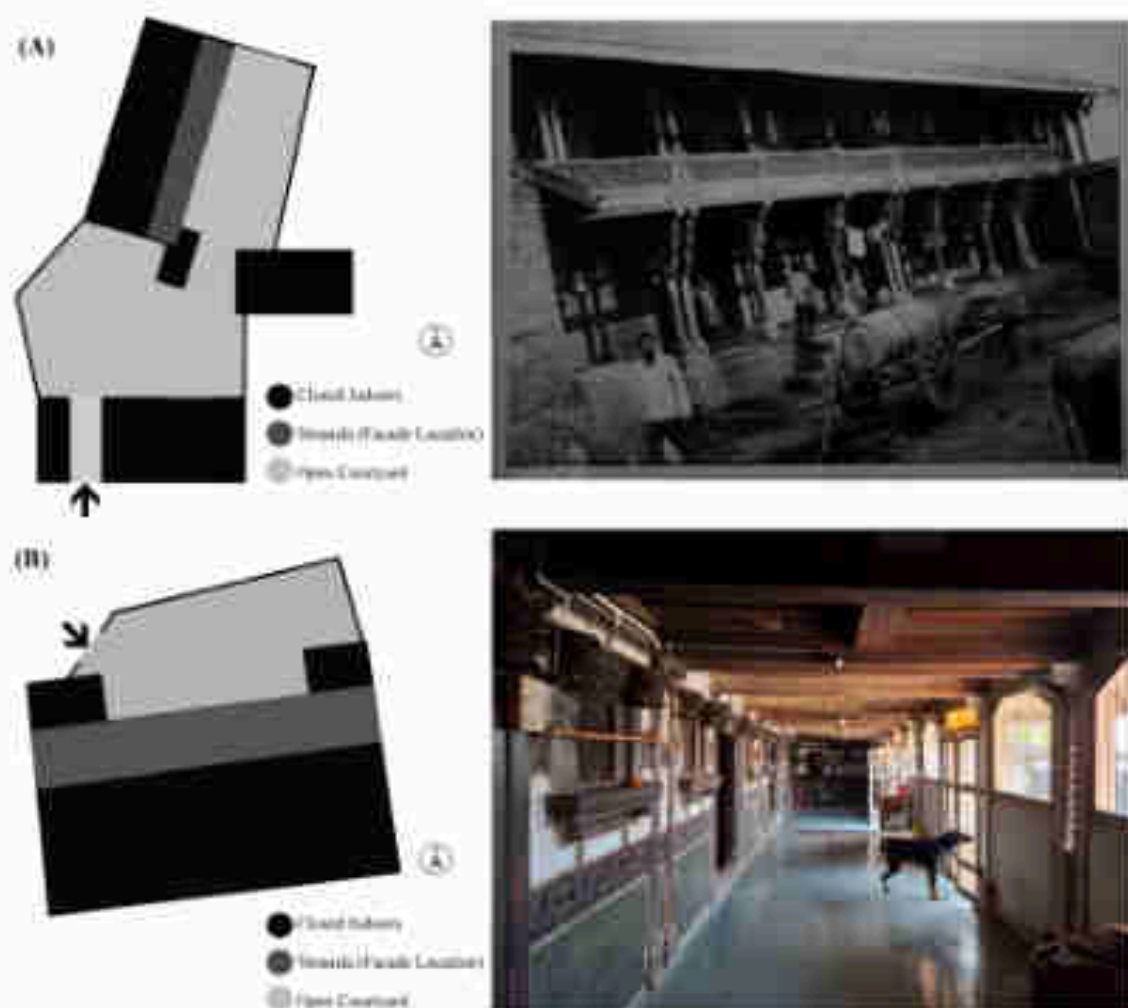


FIGURE 3

(A) Left: Major plan of dwelling complex showing the location of facade 1 (Source: Author). Right: Image of the dwelling and facade covering window space (Source: Photograph) from the dwelling owner's family album's photographic collection, May to June 1990. (B) Left: Major plan of dwelling complex showing the location of facade 2 (Source: Author). Right: Image of the window space (Source: Photograph) by author, October 2016.

abode was the wood-crafted entrance facade of the main building, where exposed timber frames, structural elements, door frames, doors, and windows are decorated with motifs and patterns inspired by the nature and culture of the region (shown in Figure 1). As a result, the wood-crafted entrance facades of the main building from two different 'Dolo' units belonging to the Rajput families from Fedara and Anbhi (as shown in Figure 2) villages in the Bhil region in the Ahmedabad district are documented and analysed as case studies in this research. The oral evidence establishes the minimum average age of these wooden buildings as 150 years.

The reason for choosing these cases stems from the fact that the Bhil region is rapidly urbanising as a result of the Dholera SIR (Special Investment Region), a government project aimed at developing a smart industrial city in the vicinity. This development, although aiming for economic and social balance, indicates a change in rural land use and livelihoods, reshaping traditional practices of the region to meet industrial and urban demands. The emergence of such new urban forms has significant implications for HNCs and the sustainable future of the region. Thus, to effectively address the changing

rural-urban dynamics in Bhil and to incorporate socio-ecological, context-sensitive design approaches into these future developments, it is essential to analyse and learn from the vernacular architecture of the region. The decision to study only two entrance facades of vernacular dwellings is to enable in-depth analysis and is based on their repetitive spatial and formal characteristics that make the selected cases representative examples of the broader regional socio-ecological design sustaining HNCs. It also stems from the fact that there are very few examples left in the region that still adhere to this traditional vernacular style, as most have transitioned to an international style, imitating the European domestic structure known as the 'Bungalow', which is regarded as a symbol of modernity.

3.3 Data collection

Fieldwork was conducted in May 2023 (Summer) and October 2024 (Winter), using the village of Fedara as a base. Both dwellings were visited during these periods, and data were collected through site

immersion by triangulating photographs and sketches with observations. Around 3 days, on average, were spent by the principal investigator (PI) at each site during both field visits documenting the entrance veranda, gathering primarily visual data with some textual observational notes. The visits at two different seasons facilitated detailed observations over time, allowing for a deeper understanding of the setting, building trust with inhabitants, and consistently repeating the data collection process central to the case study to prevent any misinformation. Triangulation enhanced the validity, reliability, and legitimacy of the collected data, allowing for a more comprehensive documentation of the vernacular façade by capturing and interpreting its spatial and artistic characteristics. The visual documentation methods also facilitated the recording of data and information, which allowed for the creation of proportionate base drawings of the entrance façades after returning from the field. These drawings aided in the visual analysis of façades to examine the role of these artefacts and their artistic features in connecting the inhabitants with nature, both physically and symbolically.

3.4 Method of analysis

Four areas of the artefact analysis method were employed to address the questions: what types of HNCs are mediated by the spatial features, and what types are nurtured by the artistic features of the entrance façade? Each of the two cases was visually analysed, and its features and patterns were interpreted for each of the four areas articulated by [Shiller \(2011\)](#). These interpretations were also supported by referring to a group of patterns (specifically patterns 95–253) which shape individual buildings as described in “A Pattern Language” by Christopher [Alexander et al. \(1977\)](#) (discussed in Sections 4.1–4.3). Further, the grounded theory technique of coding was employed following visual analysis to interpret HNCs as a phenomenon and to inductively identify patterns and types of HNCs mediated by the art and design of entrance façades in vernacular dwellings. Based on the results of grounded theory, the authors used thematic analysis to further synthesise the types of HNCs and develop a relational analysis framework from the study.

4 Case study analysis

In accordance with the research method, this section will visually analyse the two selected cases from a relational design perspective, following the structure of the four areas of artefact analysis. As per the focus of this research, the analysis will explore the spatial and artistic features and patterns of the entrance façades to demonstrate their role in HNCs. For ease of reference, the dwelling in Fedara will be referred to as Façade 1, while the dwelling in Ambli will be referred to as Façade 2.

4.1 Conditions for existence

4.1.1 Spatial

The observation of the cases suggests that the entrance veranda, featuring artistic wood-crafted façades, is typically encountered as a spatial element within the main building unit. This artefact serves as

a transitional space that connects the main building (pattern 99) ([Alexander et al. 1977](#), p. 485) with the contained open yard in the ‘Dela’ complex (pattern 95) ([Alexander et al. 1977](#), p. 488), as illustrated in the master plans in [Figure 2](#). It highlights the main building as the soul of the group that houses the most essential function in the complex and helps in creating the positive outdoor space (pattern 106) ([Alexander et al. 1977](#), p. 517) by opening to the central courtyard. The existence of these artefacts in a spatial context, viewed through the lens of HNCs, reveals that they are a semi-open interface designed in response to the socio-cultural rhythms of the family’s agrarian lifestyle. The sheltered yet open design of these spaces traditionally fosters a deep connection between the occupant’s daily activities and the rhythms of nature. For example, during a visit to façade 2, the drying of chillies was observed, which was planned according to the availability of sunlight in the space. Additionally, the space was also observed supporting informal gatherings and interactions with neighbours or between family members, especially during the cooler evening temperatures, thus acting as a common area at the heart (pattern 129) ([Alexander et al. 1977](#), p. 619). Its openness of structure is inviting for non-human others—birds, insects, etc., which were seen as dwelling in these spaces. Thus, it acts as a bridge between nature and culture, creating a space of pause that can stimulate the senses of individuals to reflect on their connection to and reliance on the natural world. In addition, these façades also play a pivotal role as climate-conscious artefacts in the hot and dry climate of Rajasthan. It connects enclosed spaces with the natural environment, acting as a liminal space that regulates the dwelling’s microclimate by providing shade and ventilation, while also shielding the interiors from direct sunlight and rain. Thus, it promotes sensorial and physiological comfort as well as supports the conscious experience of entering a building for inhabitants from the uncontrolled natural world into the controlled human environment. It acts as an entrance transition (pattern 112) ([Alexander et al. 1977](#), p. 548) supporting a graceful and mindful transition of one’s relative position within the larger world.

4.1.2 Artistic

The estimated age (approximately 150 years) of these dwellings suggests that these façades were crafted by local artisans of the region in the late nineteenth and early twentieth centuries and have been passed down over five to six generations in the family. The existence of artefacts in an artistic context, particularly from the perspective of HNCs, suggests that they act as a symbolic interface of interdependence. These artefacts with woodcarving primarily applied to the structural elements of façades are designed to project and transmit the values and beliefs of nature shared by both the artist and the community across generations. The diverse repertoires of ornamental (pattern 249) ([Alexander et al. 1977](#), p. 1146) forms depicting flora, fauna, and divine/mythological figures found in both cases serve as proof of this point. This diversity is a result of unique interpretations of the natural world by the artists in artwork reflecting their emotional responses, psyche and personal connection to nature. For instance, when comparing the lion motifs in façades 1 and 2, as shown in [Figure 3](#), we see two distinct creative forms of a lion’s anatomy. Instead of aiming for an exact replication, these interpretations highlight the individuality of each artist’s style and perspective on this majestic creature. Such creative interpretations, along with authentically captured emotional expressions of nature by



Figure 1
Left: Lion motif facade (L-Right): Lion motif facade (R-Source: Photographs by Author, October 2019).

artists in *facades*, *evokes visceral experiences that foster curiosity and a similar sensory connection to being in nature*, significantly influencing the viewer's perception of it. This argument can be reinforced by the personal experience of the PI during the field visit to the dwelling in Bhal. The continued interactions with the entrance facade and its artistic elements representing nature during documentation influenced PI's emotions and senses, which evoked for him a subjective feeling of being in nature when occupying this space despite being physically distanced from it. This experience illustrates how the artefacts being studied can inspire curiosity and exploration about nature in viewers through art, encouraging them to engage with the natural world in meaningful and personal ways. These artefacts also serve as a representation of the family's social and economic status, which can be noted by the difference in the intricacy of details and artistry in the carvings of the facades between the two cases.

4.2 Descriptive analysis

4.2.1 Spatial

The entrance veranda consists of two distinct layers, as illustrated in Figure 1. The front layer showcases a combination of intricately crafted columns, brackets, beams, balustrades, and jaalis where the structure seems to follow social space (pattern 203) (Alexander et al., 1977, p. 940). In contrast, the back layer features a thick wall (pattern 197) (Alexander et al., 1977, p. 918) adorned with curved wooden structural bands, doors, windows, lintels, sills, and niches. A comprehensive analysis of the materials and elements comprising each layer of the facades is presented in Table 2. The *teak wood* is the primary material used to create these artistic thresholds, in addition to sandstones, iron, beams, and brick masonry plastered with lime. These natural materials have unique textures and visual patterns that promote both tactile and visual interaction, creating a direct sensory connection with the natural world. Additionally, these materials contribute to microclimatic regulation, acting as insulators and temperature buffers within the dwelling, which enhances the sensorial and physiological comfort in the interiors. Thus, they are good materials (pattern 207) (Alexander et al., 1977, p. 935) that are also observed to be ageing gracefully as they expand, contract, and weather over time and with changing seasons. For example, the sandstone bases of the columns in both cases are weathered due to rain exposure, while the wood has developed shallow surface cracks in various parts of the facade as a result of prolonged sunlight exposure. This process

gives the facades a dynamic, almost living and breathing quality. Such time-based transformation of these facades offers visual cues that hold the possibility to subconsciously connect inhabitants to the familiar cycles and rhythms of nature as well as to the idea of impermanence. As Alexander (1979) states, a building that is whole must always reflect the character of nature. Since nature itself is inherently transitory, this character cannot emerge without the awareness and acceptance of death. This subconscious connection is further reinforced by the standardised, repetitive placements of the elements on the facade (shown in Figure 3), creating a column space (pattern 226) (Alexander et al., 1977, p. 1044) cohesive visual harmony echoing the natural order within the dwelling.

4.2.2 Artistic

The artistic elements forming the entrance facades in both cases can be categorised and described into three types based on the process of carving—relief carving, chip carving and sculptural carvings. The intricacy of details in the facade leaves room for interpreting that these processes of carving could have been slow and meditative, serving as a ritual for the craftsman to search for their own identity and place in the world. It reflects a conscious dialogue between the artisan, the mineral, and the natural world, whether through the reinterpretation of natural forms in relief carving or by the echoing of mathematical principles and geometric patterns found in nature in chip carving or in the sculpting of anatomy, posture, and expressions of human, animal, or hybrid forms within the wooden facades. These processes allow the artist to connect deeply with nature at material, sensory, and intellectual levels, fostering a profound appreciation for the beauty and complexity of the natural world. Furthermore, when describing the types of ornamentation on the facade, the two categories of motifs and patterns proposed by (Gallati 2004) remain applicable to the cases under study. Motifs are found as isolated units in various sizes and forms on these facades, typically depicting animals, birds, gods, flowers, and more. They are commonly visible on wooden bands, columns, and brackets. In contrast, patterns are infinite in nature and take the form of continuous bands that extend from one edge to another within the elements of facades. They are commonly encountered as part of lintel bands, window sills, and door and window frames that act as thickened edges (pattern 225) (Alexander et al., 1977, p. 1059). These forms of embellishment hold the potential to tap into our deep-seated imaginations and memories of connection with the natural world. When viewers encounter ornamental (pattern 249) (Alexander et al., 1977, p. 1146) motifs that represent animals or



FIGURE 3

(A) Facade 1 depicting the layout and rhythm of elements in facade 1. The repetitions of these elements forming the rhythm are marked with repetition of color entries. (B) Facade 2 depicting the layout and rhythm of elements in facade 2. The repetitions of these elements forming the rhythm are marked with the repetition of color entries. (Source: Author)

patterns that resemble leaves, it evokes a visual familiarity that creates a bridge between the artwork and the viewer's personal experiences in/with nature. For example, during the documentation of facade 2, when the PI encountered the motif of a snake (shown in [Supplementary Appendix 1](#)), it triggered a memory of a personal experience from his childhood when he accidentally tried to pick up a snake, mistaking it for a rope.


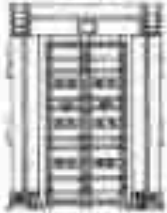

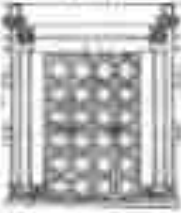








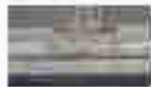





4.3 Analysis of embedded meanings

4.3.1 Spatial

According to the cosmocentric worldview prevalent in India, the entrance facades are prescribed a symbolic meaning of a spatial passage between the sacred and secular. Crossing the threshold when entering or exiting a dwelling is thus compared with navigating the spiritual and physical realms of existence ([Bhattacharya, 2015a](#)). As a result, the entrance transition (pattern 112) ([Alcazar et al., 1977](#), p. 348) facades are believed to absorb negative energies, sanctify the space and provide protection to those who enter/exit the space and inhabit dwellings, through their spatial characteristics, intricate embellishments, and orientation with respect to cardinal directions.









This is evident in the cases being studied. Facade 1 is oriented towards the east, the direction of the rising sun, which is believed to bring prosperity, good health, and positive energy into the dwelling. In contrast, Facade 2 is oriented to the north, traditionally believed to promote mental peace, tranquillity, and positive energy within the home. These orientations are also a climate-sensitive approach, making the east and north walls more open to light and air, insulating that the south and west are heat-gaining directions ([Pacheco et al., 2006](#)). This creates a comfortable outdoor room (pattern 63) ([Alcazar et al., 1977](#), p. 764) for spending extended periods in these spaces, promoting sensory comfort and a sustained connection with surrounding nature. In addition to this, the arrangement of various ornamented (pattern 249) ([Alcazar et al., 1977](#), p. 1146) motifs in the veranda, the daily ritualistic practices performed by the inhabitants in this space, and its semi-open design that provides a broader view of the surroundings all contribute to its embedded meaning of protective structure within the dwelling. As seen in the case of facade 1, the *dwarapalas* (door guardians) are positioned as brackets flanking both ends of the entrance veranda (shown in [Figure 1](#)). These figures are represented as formidable warriors armed with weapons, symbolically serving the role of shielding the space from negative energies, malevolent entities, and intruders, whether

TABLE 2: Materials and elements including HNCs in facades

Material name	Elements: Facade 1		Elements: Facade 2		Properties/Characteristics that sustain HNCs
	Front layer	Back layer	Front layer	Back layer	
Wood	<p>Column</p> 	<p>Door</p> 	<p>Column</p> 	<p>Door</p> 	<p>Natural veins and texture express the essence of the living natural world; the artisans have crafted it quite artfully. Wood has developed shallow surface cracks as a by-product as a result of prolonged sunlight exposure.</p>
	<p>Bracket (Diagonal Carving)</p> 	<p>Window</p> 	<p>Bracket (Diagonal Carving)</p> 	<p>Window</p> 	
	<p>Bracket and Arch</p> 	<p>Column</p> 	<p>Frame</p> 	<p>Column</p> 	
	<p>Beam</p> 	<p>Structural Bands (Relief Carving)</p> 	<p>Beam</p> 	<p>Structural Bands (Relief Carving)</p> 	
		<p>Beam</p> 		<p>Beam</p> 	

(Continued)

TABLE 2 (Continued)

Material name	Elements: Façade 1		Elements: Façade 2		Properties/characteristics that sustain HNCs
	Front layer	Back layer	Front layer	Back layer	
Sandstone	Column Base 	NA	Column Base 	NA	It was originally carved like other wooden elements, but it has weathered over time, upholding the natural world's order and impermanence and its constant state of flux.
Iron	NA	Window Screen 	NA	Window Screen 	Security and privacy; patterns of the window screens almost create the illusion of sunlight passing through the leaves of trees within the natural architectural space.
Iron	NA	Door Knobs and Hooks  	NA	Door Knobs and Hooks  	Elegant, attractive weight, and a warm feeling when touched, create a sense of comfort and enhance the feeling of holding a smooth mass.

(Continued)

Table 2 (Continued)

Material/ Motif	Entrance 1: Facade 1		Entrance 2: Facade 2		Presentation/ characteristics that sustain HNCA
	Front layer	Back layer	Front layer	Back layer	
Back blazney with Lion House	NA	NA	NA	NA	Regulate outdoor temperature, providing a shade before setting during hot seasons. The lion house perfectly complements the wooden facade, reflecting a vivid atmosphere
					
		NA	NA	NA	Well role as a later addition or upgrade to the

physical or spiritual. In the case of facade 2, residents were observed participating in morning rituals that involved worshipping a motif of Lord Ganesha crafted over doors and drawing a Swastik symbol on the base of doors, which is widely considered a way to sanctify the entrance and invite positive energies. These practices performed by the inhabitants at the entrance facade, their associated meanings and their reliance on the artefact offer a moment of reflection, fostering their personal connection with both the artefact and the natural world.

4.3.2 Artistic

The intricate carvings under study, which often feature natural motifs, divine figures, and patterns, are designed to celebrate the life-giving energy of nature, improve the well-being of the inhabitants and create a sense of protection and tranquillity within the dwelling (shown in [Figure 5](#)). These motifs and patterns on the entrance facade traditionally held deep cultural and social significance, infused with unique spiritual and symbolic meanings, serving as a constant backdrop in the daily lives of the inhabitants. While the local narratives associated with these artefacts are lost to generational amnesia, the traditional symbolic meanings of each artistic element can be deciphered from relevant secondary sources and texts, as presented in [Supplementary Document 1](#) and summarised in [Table 3](#). These meanings highlight the efforts of traditional humans, of both the artists and the clientele, to aesthetically and culturally interpret the natural world and its forms within the entrance facade. It acts as a symbolic communicator and serves as a gateway to the past, expressing ancestral wisdom, cosmological beliefs, and human kinship with nature while prompting inhabitants to rethink and comprehend their position in the natural world. Exploring these artistic expressions and their associated symbolic meanings in the entrance facade on an everyday basis can provide aesthetic receptivity towards nature. It can also shape an individual's perception of nature by promoting an understanding of its elements from a cosmological or spiritual perspective through art. In addition to these traditional symbolic meanings, the artefact also offers opportunities for a variety of interpretations. It enables individuals to engage with its motifs and patterns in a personal and imaginative way, fostering a deeper connection with the natural world. For example, when the motif of the monkey from facade 1 (shown in [Figure 7](#)) was interpreted independently by the authors, it led to three different associations. The first author made an anthropomorphic association through the memory of monkeys stealing vegetables from his home. In contrast, the second author associated monkeys with the emotions of joy and regarded them as symbols of guardianship, seeing them as visitors of the place. Meanwhile, the third author connected monkeys with the concepts of interdependence and kinship, viewing them as part family and part guardians who share the bounty of the landscape of Bhul. Such spontaneous and subjective interpretations of the manners of artistic facades can be seen as stemming from an individual's imagination or perceptions, which are shaped by their socio-cultural background, prior interactions with nature, or philosophical beliefs.

4.4 Distanced structural analysis

4.4.1 Spatial

The artefacts in question are a spatial element of vernacular architectural spaces. Thus, it can be inferred that they have emerged as a result of a collaborative construction process involving clientele,



FIGURE 7
 Wooden frieze of the typical 2-story vernacular building. Photograph by Author. Nov. 2021.



FIGURE 8
 Vernacular hybridization of the facade of Bhul. Photograph by Author. Nov. 2021.

carpenters, and masons in the Bhul region. Consequently, the process would facilitate the exchange of values, beliefs, and ecological knowledge, leading to a material culture that reflects the psyche or collective mind of a community toward nature. As the inhabitants take an active role in designing and building these artifacts, they gain a deeper understanding of the natural materials used and develop a deeper aesthetic receptiveness to the artistic forms representing nature. The design and building processes of these artifacts are typically rooted in generations of accumulated knowledge about the local climate, landscape, and available resources. These artifacts are also passed down through generations, serving as a symbol of collective identity. Thus, in subsequent stages of consumption, communicative value endures through these artistic facades as they become a carrier of messages from the past. As a result, it has the potential to deepen the inhabitants' understanding of and respect for the natural forces shaping their lives and dwellings. Having said that, since the British regime, the sea trade system in the region has declined, leading to a reduced availability of wood and a decrease in the practice of wooden architecture. This transition is further

accelerated by a modernization-driven mindset, homogenization of architectural forms and the availability of newer materials like concrete, steel, etc., for construction in the villages of Bhul. It has led to the creation of a more consistent sensory environment, which is more uniform in terms of materials, lighting, colour palette, etc., reducing the impact of these transitional moments and resulting in a loss of a sense of threshold. Though spatially, the entrance veranda is visible as an element in the newly built forms within these villages, the materiality, the artistic forms and the aestheticised nature that provided the living quality to these artifacts have disappeared in the newer forms. Additionally, changing family structures are also affecting the existing vernacular facades with extensions and partitions carried out within the dwelling, not following the traditional style to accommodate family needs. This has resulted in the vernacular hybrid forms, specifically visible in the case of facade 1, shown in Figure 8. These transitions suggest that while the thresholds retain their functional significance, they have lost their symbolic value, which once subtly reinforced personal and spiritual human connectivities with the natural world.

4.4.2 Artistic

Since the artifacts under study were originally crafted in generations ago, specific evidence about the local artisan community that created them remains elusive. Given the expertise and knowledge required for wooden construction and carving, it can be inferred that local carpenters (known as *uthans*) primarily would have undertaken the work of executing these artifacts. The secondary sources also suggest that the *Mesudas*, a community of carpenters renowned for their proficiency in wood carving, may have been the ones behind these creations (Thakkar, 2003). While created by individuals, as already discussed before, these artifacts are also shaped by the intangible forces of culture, the collective beliefs and values towards the nature of the community. Traditionally, artistic creation is likened to cosmic creation. In this analogy, cosmic elements serve as the foundational building blocks for producing art, and the process involves ordering chaotic materials to give them form, with the ultimate goal of achieving spiritual fulfillment through the process (Crombag and Buzza, 1987). According to this perspective, artists can be seen as divine creators who bring their imagination to life through spontaneous conception and personal inspiration from nature. They use the grammar of form, lines, and geometric shapes to imitate the forms of nature, creatively rather than passively, in their artistic articulation. Thus, when viewed from a distance, the main line of the facade intrigues the spectator's eye and mind, and as one moves closer, the composition of elements and materials that comprise the artifact becomes more apparent, and further closer observation reveals its elemental and essential details and meanings of carved surfaces. The making process allows the artisans to connect with nature through their imaginations and processes of artistic articulation, which, in turn, through the process of observation, can also influence the inhabitants in a similar manner. For example, again taking the motif of monkeys in facade 1, as shown in Figure 7, they are depicted carrying vegetables, which can be an imaginative personification of the spring season, representing a good harvest or a symbol of prosperity. Unfortunately, this intricate art of wood carving in dwellings is on the decline due to the changing economic as well as architectural landscape of the region. Wood carving skills were traditionally passed down through generations, but with increasing alternative economic opportunities, younger generations of these artisans opt for more profitable professional careers, resulting in a significant loss of knowledge of craftsmanship in the region. This is further yed by the changes in construction materiality, which have fostered the decay in the practice of making traditional motifs and patterns that were once integral to the facades of dwellings.

This analysis presented various connections with nature mediated by spatial and artistic features. Although the artistic and spatial components of facades are analysed separately here, their interconnection became evident during the analysis. It is important to study these elements in tandem to fully understand the phenomenon of HNC in vernacular facades. Following this, the Section 5 will focus on synthesising the analysis to present the results and discuss the thematic levels of HNCs fostered by the facades.

5 Results and discussion

The two selected entrance facades serve as examples to illustrate how spatial and artistic features can promote HNCs within dwellings,

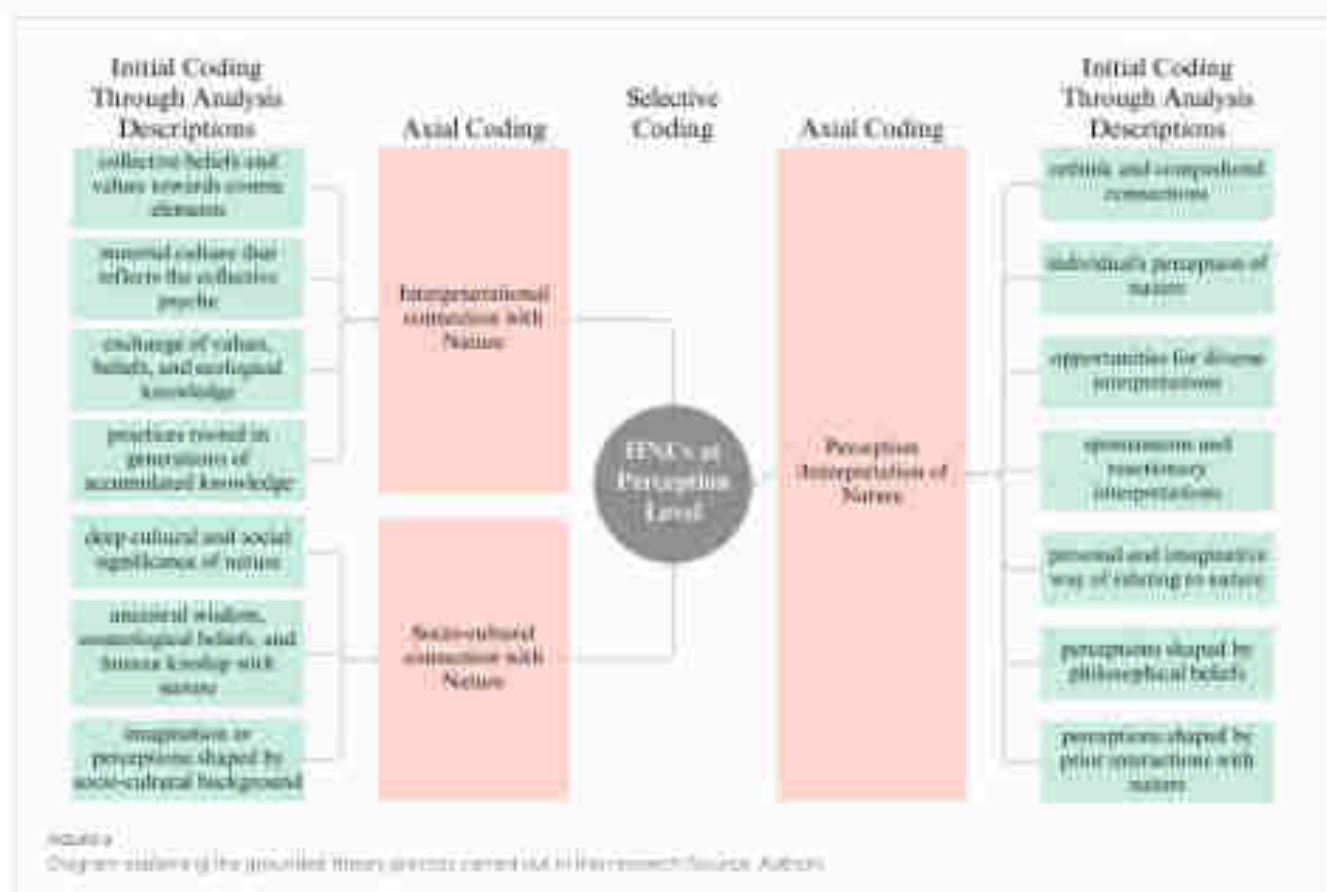
TABLE 4 Coding and identifying HNCs

Actual codes of HNCs	Selective codes of HNCs
Bioclimatic connections Material utilization connections Empathetic connections	HNCs at material level
Direct nature connections Future engagement connections Connections by repetition/variation with nature Connections by spatial relationship with nature	HNCs at emotional level
Psychological connection to nature Nature as imaginative representations Vividness connections	HNCs at imaginative level
Extreme reflection of nature in design Symbols, emotional, or intellectual connections through articulation Knowledge based connections with nature	HNCs at artistic/articulation level
Symbols, emotional, or intellectual connections through interpretation Spectral connections with nature Aesthetics, understanding/appreciation of nature	HNCs at aesthetic/interpretivity level
Temporal connections with nature Familiarity with natural order	HNCs at familiarity level
Personal connection with nature Epistemological connections with nature	HNCs at personal level
Socio-cultural connection with nature Perceptual interpretation of nature Intergenerational connection with nature	HNCs at perception level

contributing to sustainability transitions. First, the results will be discussed, emphasising the various levels of HNCs influenced by design and embellishments in the cases (Section 5.1). Subsequently, the discussion will focus on proposing a relational analysis framework and guideline by thematically synthesising the results of the analysis (Section 5.2).

5.1 Types of HNCs

The various connections fostered by spatial and artistic characteristics outlined in the case studies (Section 4) were initially coded to identify concepts related to HNCs in the facade. This process revealed several key concepts, including: "connecting daily activities with the rhythms of nature," "personal connection to nature," "creating a direct sensory connection," "linking to familiar cycles of nature," "connection to natural materials," and "imaginations and memories of nature," among others. The initial concepts were further organised through axial coding that established 23 large categories, as discussed in Table 4. Eventually, through selective coding, eight thematic levels of HNCs were identified, which are influenced by the spatial and artistic features of the facade. The proposed theory process followed for emerging these themes is shown in an example of perception level HNCs in Figure 8. Each of these categories is discussed in this section.



Four of these categories also directly correspond with the existing 4 of the 14 patterns of HNCs proposed in Biophilic Design by [Karr-Saunders et al. \(2014\)](#); these connections are also discussed here.

- HNCs at Material Level:** This category refers to the physical connections with nature that are mediated by the material characteristics and their conscious utilization in an artefact. As discussed in the cases studied, this includes visual and tactile connections fostered by textures and organic patterns of materials, microclimatic regulation through materials and material empathy in the process of artefact creation. It reflects the 'material connection with nature' pattern of biophilic design, emphasizing the use of natural materials in the built environment to represent local geology or ecology, thereby creating a distinct sense of place ([Karr-Saunders et al., 2014](#), p. 40).
- HNCs at Sensorial Level:** This category pertains to physical connections with nature facilitated by the design characteristics that stimulate human senses in an artefact. It includes sensorial connections fostered by the spatial quality of the artefact, visceral experiences of art forms, poses and movement within the artefact and processes of embodied creation of artefacts. It corresponds to the 'non-visual connection with nature' pattern of biophilic design, which is defined as auditory, haptic, olfactory, or gustatory stimuli in the built environment that engender a positive reference to nature or its systems and processes ([Karr-Saunders et al., 2014](#), p. 26).
- HNCs at Imaginative Level:** This category refers to an artefact's ability to transcend sensory, spatial, and temporal limits, stimulating imagination and provoking memories to connect

with nature. In the cases examined, this includes vicarious connections developed by processes of imagination in the creation of artefacts and interpretation and reminiscence of natural motifs and patterns in the artefact.

- HNCs at Artistic Articulation Level:** This category pertains to the symbolic, emotional, or intellectual connections with nature facilitated during the creative articulation of artefacts. As discussed in the studied cases, it includes expressive connections emerging during the creative articulation of emotional responses to nature, the capturing of emotional expressions of nature, or the embedding of the symbolic values of nature by the artists within the artefact.
- HNCs at Aesthetic Receptivity Level:** This category refers to the symbolic, emotional, or intellectual connections with nature fostered by the aesthetic receptivity of artefacts. This includes explorative connections fostered by active collaboration of inhabitants and artisans in the design of artefacts, attentive exploration of artistic forms and deciphering the traditional meanings associated with art and artefacts, as demonstrated in the analysis of cases. It reflects the category of 'biomorphic forms and patterns' in biophilic design, emphasizing symbolic references as built spaces to the contained, patterned, and textured arrangements that are prevalent in nature ([Karr-Saunders et al., 2014](#), p. 30).
- HNCs at Familiarity Level:** This category refers to the subconscious connections with the cycles and rhythms of nature, influenced by the compositional and transformative qualities of artefacts. In the context of the cases, this includes familiar connections evoked by the ageing and weathering of

materials over time in artefacts, the standardised, repetitive arrangement of structural elements, and the visually recognisable composition of natural motifs and patterns. It corresponds to the 'connection with natural systems' category of biophilic design, which emphasises awareness of natural processes, particularly seasonal and temporal changes in ecosystems within the built environment (Holling et al., 2021, p. 36).

- vi. *HNCs at Personal Level*: This category pertains to the personal connections with nature developed through spontaneous or reactive creation and interpretation of the characteristics of artefacts. In the cases examined, this includes personal connections established through spontaneous conception and interpretations of nature in the creation of these artefacts, curiosity-driven interpretations of various expressions of nature in artefacts and the practices performed by individuals concerning nature within the context of the artefact.
- vii. *HNCs at Perception Level*: This category relates to the perceptual connections with nature that are shaped by the socio-cultural or philosophical creation and interpretation of the characteristics of the artefacts. As discussed in the examined cases, it includes the phenomenal connections that arise during the designing of the artefact responding to the socio-cultural rhythms of the family, cosmological or spiritual interpretations of various artistic expressions of nature found in the artefacts, and personal interpretations of artistic facades influenced by socio-cultural or philosophical beliefs of an individual.

5.2 Relationality: guidelines and analysis framework

The results indicate that the vernacular facades foster multiple levels of HNCs (as discussed in 5.1), highlighting the importance of spatial and artistic features in shaping these relationships. Based on the analysis of the vernacular cases, five fundamental guidelines for the relational design of architectural thresholds, specifically facades, can be provided as a means of effectively enhancing human-nature connections. The guidelines are as follows:

1. The representational expressions of nature in facades should be diverse, recurrent, themed, abundant and place-based (inspired by local flora and fauna) to immerse inhabitants in echoes of the natural world. The greater the variety of living patterns in a space, the more it feels alive as a whole, creating a self-sustaining energy that integrates the building with nature (Alexandrie, 1979).
2. The artistic forms and spatial characteristics should be intervention as 'patterns of relationships.' Each unique configuration of artistic patterns should rely on spatial patterns to thrive, creating a profound aesthetic experience of nature in the daily lives of the inhabitants.
3. The ornamental forms of nature in facades should also have a clear and definite function within a building. As observed in the case studies, the artistic forms can be typically integrated as part of the structural elements of the building, door frames, windows, balconies, balustrades, etc.

4. As Alexandrie (1979) states, a building that achieves wholeness must embody the character of nature, which inherently includes processes of decay and death. Accordingly, the materials used for thresholds should be carefully selected so that they weather and age gracefully, thereby evoking the sense of impermanence within inhabitants that lies at the heart of the natural world.
5. In creating patterns and motifs inspired by nature, architects and designers should step back and trust the artist's spontaneous conception and personal interpretation of natural forms to guide the design. This approach ensures variation and uniqueness in how patterns manifest while being repeated, following the generative logic of nature itself.

In these cases, it was observed that the art of wood carving evokes feelings of awe, wonder, and reverence, often triggering memories that connect one emotionally to the natural world. At the same time, its spatial qualities create a multisensory experience, encouraging one to engage with nature in a present and embodied way. These entrance facades thus play a crucial role in connecting people with nature both internally and externally in everyday life and thus hold the potential for sustainability transitions. Therefore, it's important to emphasise that architectural design—whether in urban or rural areas—should prioritise careful design of facades and thresholds, as they play a vital role in maintaining HNCs. These elements enhance the aesthetic appeal of buildings and contribute to the overall harmony between architecture, inhabitants and the natural surroundings. However, current architectural research lacks a framework for examining how transitional architectural spaces, such as verandas and entrance facades, facilitate embodied and emotional connections between humans and the natural environment. This poses a risk of these traditional architectural elements disappearing without a comprehensive understanding of their relational and symbolic significance, due to increasing standardisation and the loss of vernacular practices. Recognising this loss, we developed an initial framework by thematically synthesising the analysis and results of this research, as shown in Table 1.

Derived from the methodological approach of this research, this framework is intended to be utilised by architects and researchers for further studies of architectural facades and their role in HNCs. This framework will potentially also assist sustainability researchers, transition researchers and artists in understanding the integration of art and architecture for reconnecting humans with nature.

From this research, it can be stated that these relationally designed elements in architecture can contribute to inner transformations (Lee et al., 2022; Lee et al., 2020) which focus on helping fundamental shifts in the interior dimensions of sustainability, such as values, beliefs, worldviews and inner capacities. Furthermore, the results also provide a significant contribution to studies on the interconnection of connectedness with nature, living in crisis (Schubert et al., 2022), and holistic well-being (Chakrabarty, 2022) and biophilic design (Salfer et al., 2011). Urbanisation is considered to have resulted in a loss of direct contact with nature, leading to an 'extinction of experience' and human-nature disconnection (Soga and Gamm, 2016; Gamm et al., 2014). The guidelines derived by analysing thresholds in vernacular dwellings that maintain HNCs can be integrated into a current sustainable development model for housing and urban planning to 'revive the experience' of nature in the towns and cities.

TABLE 3 Relational analysis framework for HNCs.

Components	Level of HNCs	Characteristics of artefacts to be analysed
Physical	Material level	Analysing material, spatial and artistic characteristics of artefacts that mediate human senses of form a physical connection with nature
	Sensory level	
Creative	Imaginary level	Analysing process of creative articulation of artefacts that stimulates imagination and provides memories to foster symbolic, emotional, or intellectual connections with nature
	Artistic articulation level	
Communicative	Familiarity level	Analysing the communicative strength of an artifact in nurturing sensory receptivity and familiarity with the natural rhythm to foster subconscious connections with nature
	Aesthetic receptivity level	
Interpretive	Personal level	Analysing spontaneous or socio-cultural interpretations of nature in artefacts that foster personal and perceptual connections with nature
	Perception level	

Source: Authors

6 Conclusion

There is a lack of research investigating vernacular architecture and its entrance thresholds from a relational perspective, despite their critical role in connecting humans and nature within the built environment. Investigating these spaces can provide socio-ecological design perspectives and valuable guidelines for transforming societies toward a relational ontology and facilitate the transition to sustainability through architectural design. The present research aimed to explore the HNCs mediated by the entrance facades in vernacular dwellings in everyday life, studying two wooden vernacular facades in the Bhil region of Gujarat, India. It explored the key question of what types of HNCs are fostered by the spatial and artistic features of the entrance facade, acting as a relational design element within vernacular dwellings.

Based on this qualitative study, the authors found that entrance facades operate as physical and symbolic relational space, fostering eight levels of HNCs—material, sensory, imaginative, artistic articulation, aesthetic receptivity, familiarity, personal, and perceptual, which enhance the ecological consciousness of the inhabitants. Through a complex interplay of orientation, materials, and spatial form, combined with artistic features that represent the natural world, these elements serve as visual and tactile reminders of one's place within a larger ecological system. Together, the entrance facade's spatial and artistic elements create an intertwined design system, which, on one hand, develops a porous boundary that facilitates sensory and experiential engagement with the surroundings and, on the other hand, encodes collective mindsets, cultural narratives, traditional ecological knowledge, and cosmological beliefs, fostering philosophical and emotional connectives with nature. This analysis posits the hypothesis that designs of vernacular entrance facades offer multiple opportunities for both internal (philosophical or cognitive) and external (experiential or material) HNCs and can thus act as a leverage point for sustainability transitions. This multiplicity highlights the role of these elements as active contributors to relational ontology, yielding essential insights for socio-ecological design that is grounded in the cultural and ecological context of a place.

Further, the guidelines and analysis framework proposed within the study synthesise the research findings, laying out tools for relational design application as well as effective analysis of architectural thresholds as spaces for HNCs. However, it goes beyond the scope of this paper to provide a comprehensive set of guidelines and an analysis framework for HNCs. Instead, it encourages researchers to challenge convention by bringing together the disciplines of architecture and sustainability transitions for HNCs. It reimagines and represents

vernacular architecture as a key exemplar of designing 'relationally'. Thus, future studies can refine the proposed guidelines and framework by applying them as part of the architectural design process or examining other vernacular spaces. Also, this research engages with scholarship on biophilic design and pattern language; however, the mathematical analysis of vernacular patterns to understand their role in strengthening the bond between individuals, their surroundings, and nature lies beyond its scope. Future studies could extend in this direction to deepen the understanding of these patterns through mathematical approaches.

While the sample of two dwellings is contextually representative, the localised focus of this research limits the capacity to make broader generalisations and the potential transferability of its results to other cultural and geographical contexts. Therefore, future research should include additional case studies of diverse vernacular practices across India, explore similar artistic thresholds in urban vernacular settings, or conduct a comparative analysis of threshold designs across different cultures and countries. This would help in the development of universal design guidelines for architecture to foster HNCs and relationality in the context of sustainability transitions. Additionally, access to well-preserved vernacular dwellings with their original entrance facade elements in an unaltered state is limited, as many of these spaces (seen in facade 1) have been adapted and modernised. Studying these transitions within vernacular spaces from a relational perspective is also essential to further understanding changes in human perception of and relationships with nature. By integrating these lessons, newer architectural forms in both rural and urban regions can be designed to be more relational, thereby enhancing the HNCs and promoting a shift to more sustainable modes of living and being in/with nature.

Data availability statement

The original contributions presented in the study are included in the article/[supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

DR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. KC: Conceptualization, Methodology, Supervision, Writing – review & editing, Resources. RK:

Conceptualization, Methodology, Supervision, Writing - review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of this article.

References

- Achar, P. S. R. K. (2015). *Hindu knowledge: The study of the synthesis and meaning of Hindu*. India: Publications, (pubs). *Neemathur*. Available online at: <https://www.scribd.com/document/publication/106106106> [Accessed 23 September 2023].
- Adelstein, M. B., Zahari, K., and Mada, H. A. (2019). Architectural case study as a research method – a review. *Int. J. Urban J. Environ. Design Constr. Manage.* 15, 393–403.
- Alexander, C. (1979). *The timeless way of building*. New York: Oxford University Press.
- Alexander, C., Ishikawa, S., and Silverman, M. (1977). *A pattern language: Towns, buildings, construction*. New York: Oxford University Press.
- Althaus, S. (2021). Regenerative design: Method and its relation with Vernacular Architecture. *Konkuk University Architecture as a case study*. In 2021 International Conference on Advances of Sustainable Engineering and its Application (ICASEA). IEEE, pp. 206–212.
- Anthon, M. (2020). Human nature reconnection to city of social-ecological crisis – a relational account for sustainability transformation. *Design. People* 18, 2168700. doi: 10.1080/20597918.2020.2168700
- Basu, G. (2020). In Climate: Folk art of India and G. Basu (Kolkata: Ramen Gopal Cultural Centre, Ministry of Culture, Government of India).
- Berry, T., Bal, O. (2019). A. Gauth, S., Maurin, M., M. Ramesh, S., A. B. C. C., et al. (2023). Document from forest nature: expanding our understanding of forest-nature relations. *People* 20, 476–488. doi: 10.1002/people.10433
- Borkan, N., Ismail, S. M., Callaway, J. M., and Ali Ibrahim, N. (2023). Research trends in vernacular architecture: a bibliometric study. *ISVS e-journal* 6, 72–81. doi: 10.30845/ISVS.19031422.1907343.V1
- Bull, S. B. (2019). *Ecological balance and Eco-education for Philosophical foundations of education*. (Singapore: Springer), 117–111. doi: 10.1007/978-981-13-0442-2_33
- Burkitt, J. (2014). *Threshold space: Wabi-sabi architecture. Analysis and design tools*. Basel: Birkhäuser, Cop. De Gruyter.
- Bonilla, J. (2017). "Narrative literature review" in *The SAGE encyclopedia of communication research methods*. (Thousand Oaks, CA: SAGE Publications, Inc. pp. 1076–1077. doi: 10.4135/9781473940114.011.070
- Browning, W., Beck, C., and Chen, J. (2014). "14 Patterns of Biophilic Design: Improving Health and Well-Being in the Built Environment." *Biophilic Design* (Piscataway, New York: Taylor & Francis Group Inc. Available online at: <http://patterns.biophilicdesign.org/> [Accessed 17/2/23].
- Bull, S. (2014). Sustainable, healthy, regenerative: The potential of Wabi-sabi for urban design. *Front. Sustain.* 4, 130712. doi: 10.3389/fsu.2014.00012
- Chakrabarty, K. (2024). "Mapping the maze: a methodological framework for studying 'complexity through design forms' in South-Asian/Asian, present and future." In: P. Bhattacharya (New York: Nova Science Publishers), 37–72. doi: 10.52003/NOVSP0752
- Choudhury, J. B. (1998). Development and Distortion: wabi-sabi aesthetics cultural ecology. *Infant Lit.* 43, 172–179.
- Cilliers, E. J., Ummersmann, W., Kishi, H., and Tjebk, H. (2022). Scaling up of nature-based solutions to guide climate adaptation planning: evidence from two case studies. *Front. Sustain. Cities* 4, 850440. doi: 10.3389/fsu.2022.850440
- Cook, R. J., Oliver, A., and Robinson, J. (2013). Regenerative design: what ecological systems and co-evolution. *Built Environ.* 41, 227–237. doi: 10.1007/s10667-013-9377-0
- Cook, R., Wei, S., and Robinson, W. J. (2016). *Building as the biosphere: exploring an embodied form of relationship construction in resilience building*. *Sustain.* 8, 11, 831–842. doi: 10.3389/su.2016.01187-8
- Cremers, M. S., Perle, A., Hoffmann, E. M., Schladt, E., von Cramon-Taubadel, A., and Jacharaka, T. (2014). Implications of agricultural traditions and urbanization for ecosystem services. *Nature* 515, 34–37. doi: 10.1038/nature13443
- Dieringer, C., Shatt, D. J., Pickett, L., and von Weizsäcker, H. (2017). Assessing sustainable biophysical human-nature connections at regional scales. *Environ. Res. Lett.* 12, 055007. doi: 10.1088/1748-9326/12/5/055007
- Digital, A. (2010). *Nature in modernity: concept, culture, space or attitude*. New York: Free Press. doi: 10.1016/978-1-4319-0491-9
- Dutta, J., and Kumar, N. (2015). A comprehensive understanding of the research themes, trends and future directions of vernacular architecture using bibliometric analysis. In *Proceedings of the 2nd International Conference on Trends in Architecture and Construction*. ICTAC 2015. Lecture Notes in Civil Engineering, vol. 327, eds A. Vaidya, V. Chand, Sharma, and A. Tanti (Singapore: Springer), doi: 10.1007/978-981-07-4883-1_34
- Fujimori, I. (2022). "Nature-based solutions and biophilic design: Eco-systemic approaches to regeneration" in *The sustainable built environment between generations and generations*, eds P. Naldi, C. Aspin, and G. D. Giovanni (Palermo (Italy): Palermo University Press), 108–121.
- García, A. (1999). After nature: steps to an environmentalist political ecology. *Con. Anthropol.* 10, 1–30. doi: 10.1086/317579

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- Goodrich, A. (2000). 'Claypit & water' in *Traditions of Different Place, nowhere*, ed. B. B. B. (Durham: Duke University Press), 111–125. doi: 10.1215/9780820320410_004.
- Goodrich, A. (2018). *Design for the Planet: Radical interdependence, autonomy, and the making of worlds*. Durham: Duke University Press.
- Goodrich, A., Odetwile, M., and Sharma, R. (2020). 'Designing relationally-emerging paths toward pluralistic transition' in *Relationality: An emergent politics of life beyond the human* (United Kingdom: Routledge Publishing Plc), 151–164.
- Holmström, J. M., and Davis, A. R. (2022). 'Creating built futures for sustainability transitions' *Geogr. Compass* 16(12362). doi: 10.1111/gc.12362.
- Jalla, C., Jansen, A., Schmalzer, L., Olson, P., Carpenter, S. R., Chapin, F. S., III, et al. (2010). 'Measuring the biophysical basis' *Arch. Sci.* 41, 218–230. doi: 10.1016/j.as.2010.01.004.
- Jalla, C., Pridemore, J., Robinson, J., Kuhn, V., Weller, J., Lamm, M., et al. (2021). 'Our future in the Anthropocene' *Arch. Sci.* 42, 334–348. doi: 10.1016/j.as.2020.02.014.
- Green, R. M., Kohn, R. L., Hansen, H. H., Katschke, L., and Nordstrom, C. (2019). 'A world ecological approach to architecture and planning' *J. Archit. Environ.* 2, pp. 13–44. Available online at: <https://worldwidesustainabilityjournal.org/journal-of-architecture-and-environment/pdf/2-13-44.pdf>
- Green, R. M., Johnson, C. D., and Adams, A. (2006). 'Writing narrative literature reviews for peer-reviewed journals: lessons for the trade' *J. Clin. Stud.* 3, 101–113. doi: 10.1186/1745-6215-3-12.
- Goodman, J. I., Wilson, W., Sherry, A., Leding, J., Kozlowski, R., Fortman, A., et al. (2022). 'Architectural multiplexing building design: concepts, challenges, and design process' *Sustainability* 14(1440). doi: 10.3390/s14121440.
- Hanna, and Wernick, S. (2021). 'Comparative understanding of traditional architecture based on literature review: defining the definition of traditional architecture' *Int. J. Archit. Environ.* 1(25–262). doi: 10.22780/iaae.15252719.
- Hirayama, B. (2018). *Indian and western philosophy: a study in contrast*. CRC Press/World Scientific, New Delhi: UK/Printed.
- Hudra, I. (2021). 'Architecture as the psyche of a culture' in *The cultural role of architecture: contemporary and historical perspectives*, eds P. Lumsden, J. Lindoff and J. V. Mordant (Hoboken, NJ: John Wiley & Sons, New York, NY: Routledge).
- Horta, K., Sullivan, A., and Mann, M. (2018). 'Resilience of restoration and restoration challenges in semi-arid zones in climate change' *Sci. Rep.* 11, 9172. doi: 10.1038/s41598-021-02772-9.
- Hui, D., and Shui, J. (2022). 'Designing for being environment: using regenerative development: a case study of the podium' in *Biological design: Transforming architecture, landscape, and urbanism*, eds M. P. Zan, P. Connolly and H. Smithers (Cham, NY: Knowledge Monographs of the Taylor and Francis Group), 26–33.
- Jay, C. D., Abou, D. J., van Welyden, H., Frenken, C., Klamacki, K., and Fischer, J. (2016). 'Reconnecting with nature for sustainability' *Nature* 535, 1590–1591. doi: 10.1038/5351590a.
- Jay, C. D., Ferrel, E., and Fischer, J. (2021). 'Inside our sustainability: the tug-of-war of inner world' *Arch. Sci.* 42, 208–217. doi: 10.1016/j.as.2020.01.007.
- Jay, C. D., Gans, H., Fischer, J., Abou, D. J., Klamacki, K., Domingos, C., et al. (2017). 'Human-nature connection: a multidisciplinary review' *Curr. Opin. Environ. Sustain.* 26–27, 198–113. doi: 10.1016/j.coes.2017.10.008.
- Jay, C. D., Schepke, N., Wernick, C., and Wernick, C. (2021). 'SMAUG: sustainability: spatially multi-scale transformation in research, education and practice' *Nature* 594, 2777–2786. doi: 10.1038/s41586-021-01468-1.
- Jegathesan, K., Kijom, A., and Epeolu, S. (2020). 'Sustainability indicators for vernacular architecture in India' *Arch. Sci.* 41, 201–214. Available online at: <https://www.sciencedirect.com/science/article/pii/S0304378920300011>
- Jain, K. (2001). *Thematic space in Indian architecture*. New Delhi: India Research Press.
- Jay, A. (2022). 'Reconnecting the strength of traditional - sustainable development and vernacular architecture in India' *Int. J. Res. Sci. Eng. Res.* 4, 3696–3703. Available online at: <https://www.ijres.org/issue/2022/ijres4-04-3696-3703>
- Karim, R. A. (2000). 'Learning from vernacular architecture: sustainability and cultural authenticity' in *From architecture: A harmonization between architecture and nature*, eds G. Boudreau and C. A. Riebel (WIT Transactions on Ecology and the Environment (Hingham, UK: WIT Press), 1–11.
- Kolbert, E. R., Herzog, J., and Miller, M. (2021). *Biophilic design: The theory, science and practice of bringing buildings to life*. Hoboken, NJ: Wiley-Blackwell.
- Korke, S. A., and Wilson, S. G. (2013). *The biophilic hypothesis*, eds S. R. Kellner and E. G. Wilson (Washington, DC: Island Press).
- Kwilek, L., Goh, F. W., Kim, J., Markell, L., Ojima, R., Wernick, A., et al. (2018). 'An agenda for sustainability transitions research: view of the art and future directions' *Environ. Res.* 166, 1–32. doi: 10.1016/j.envres.2018.01.004.
- Lau, A., Dierman, J., Oosterom, T., de Gooijer, F., Aerts, F., Wang, J., et al. (2022). 'Effects of biophilic design interventions on university students' cognitive performance: an audio-visual experimental study on an interactive virtual office environment' *Built Environ.* 2021(1179). doi: 10.1016/j.builtenv.2021.1179.
- Lee, N., and Choi, N. (2021). 'Green spaces in Chinese schools enhance childrens environmental attitudes and pro-environmental behavior' *Child. Youth Environ.* 31(25). doi: 10.7326/childenviron.31.1.1891.
- Loos, R. (2000). *Lost child in the woods: Saving our children from nature deficit disorder*. London, England: Atlantic Books.
- Langer, M. (2000). *Consciousness, qualitative, Erfahrung: Methodologie, Organismus, Materialismus*. Wiesbaden: Springer-Verlag.
- Langer, M., and Froschauer, U. (2017). *Antikoloniale Organismus und Verhältnisse*. In *Die Welt der Natur*, Göttingen: Springer-Verlag.
- Markell, L., Kwon, R., and Trufes, R. (2022). 'Sustainability transitions as emerging field of research and its prospects' *Res. Policy* 41, 475–487. doi: 10.1016/j.respol.2022.102373.
- Markell, L., and Trufes, R. (2020). 'Innovation processes in large technical systems: market liberalization as a driver for radical change?' *Res. Policy* 49, 849–875. doi: 10.1016/j.respol.2020.102373.
- Marx, H. F., Marx, G., and Rapraet, C. (2006). 'Individual and relational concepts of self include and the United States' *Am. J. Child. Adolesc. Dev.* 104, 8–24. doi: 10.1002/cd.101.
- May, T. A., and Harris, C. M. (2006). 'The construction of nature only: a measure of individual's feeling in community with nature' *J. Environ. Psychol.* 31, 305–315. doi: 10.1016/j.jenvp.2006.01.001.
- McLennan, J. E. (2004). *The philosophy of sustainable design*. Kansas City, MO: Earthscan Publishing.
- Marx, G., Pundit, M. M., and Mishra, V. (2022). 'Indigenous perspectives on happiness: insights from Indian tradition' in *Marx, G., and Mishra, V. eds. I Kognition in cultural context*. Cham: Springer International Publishing.
- Mishra, A., and Rock, E. (2018). 'Society over nature as a paradox: socially implemented but ecologically reduced' *J. Environ. Plan. Manag.* 61, 994–1000. doi: 10.1080/09644067.2017.1354075.
- Muller, S. (2021). *Design ethnography: Epistemology and methodology*. 1st ed. Translated by R. K. K. Cham: Switzerland: Springer Nature.
- Muradian, K., and Odeh, R. (2021). 'Beyond ecosystem services and nature's contributions to society to leave no one in communication behind' *Ecol. Econ.* 187(107330). doi: 10.1016/j.ecolecon.2021.107330.
- Nasir, O., and Araf, K. (2021). 'Vernacular architecture as a design paradigm for sustainability and climate: the case of Lushik, India' *Int. J. Civil Eng. Archit.* 5, 214–231. doi: 10.1007/s40201-021-00073-7.
- Nasir, O., K. K. K. K., and Marjan, S. A. (2020). 'The nature of the scale: linking individuals' connection with nature to environmental concern and behavior' *Environ. Res.* 191, 113–126. doi: 10.1016/j.envres.2020.110748.
- Palmer, V. (2018). 'Climate architectural tradition of India in International Conference of "Passive and Low Energy Cooling for the Built Environment"', pp. 1123–1129.
- Pallares, J. (2021). 'The eyes of the skin: Architecture and the senses' *Architect.* 70, 504–510. doi: 10.1002/2794.10420001.
- Philosophy, M. (2018). 'Construction of vernacular dwellings: history of architecture and sustainability' in 10th International conference on the construction of monuments in the Mediterranean Basin. Cham: Springer International Publishing, pp. 163–168.
- Rahmi, S., Wilson, W., Wilson, K., Wilson, A., Chapin, F. S., III, Lamm, J., et al. (2022). 'Planning biophilic: exploring the role of the space for humanity' *Arch. Sci.* 43, 10.1016/j.as.2022.102322.
- Rahmi, S. (1994). *Architecture without architecture: A short introduction to non-pedigree architecture*. Garden City: New York: Doubleday Books.
- Rahmi, S., Campbell, L. K., Johnson, M. L., and Johnson, J. (2022). 'Evidenced the COVID-19 pandemic's transformation of human relationship with nature at multiple scales' *Front. Sustain. Cities* 4(100078). doi: 10.3389/fsu.2022.100078.
- Rahmi, S., and Nagarajan, R. V. (2020). 'Transition spaces in an Indian context' *Archit. Arch.* 6, 195–214. doi: 10.1080/24747909.2020.180078.
- Rahmi, S. L., and Paul, G. A. (2000). *The Hindu way*. (New Delhi: India: Sage, 25–78–79).
- Rahmi, D. (2022). 'The significance of some craft and architecture preserving history through evidence of painting, sculpture, and architecture' *Int. J. Acad. Res. Des.* 6, 499–496. doi: 10.13140/RG.2.2.2022.1700.
- Rahmi, S. W. (2024). 'A critical examination of domestic dwellings and value systems: exploring how culture and identity shape perspectives' *J. Urban. Resour. Develop.* 8, 79–86. doi: 10.1080/19449012.2023.2201177.
- Rahmi, R. (2020). 'Pascarella in urban manifestation: a case study of urban design' in *Proble: The urban vision: Asia in nature*, eds S. Rahmi (Hoboken, NJ: Prentice Hall), 123–130.
- Rahmi, N. E. (2021). 'Biophilic values of Bauhinia: exploring Shikharath with art' *J. Emerg. Urban. Res.* 10, 1049–1056. doi: 10.13140/RG.2.2.2021.90004.
- Rahmi, S. M. P., and Mahajan, L. K. (2022). 'Building with nature: The case of housing houses in Agaña Maori, Philippines, in December, M., and Tanno, D. eds. Sustainability and health: the nexus of urban-rural architecture and well-being. 36th International Conference of the Architectural Science Association: The Architectural Science Association (ARSA/AS), pp. 184–186.

- Kaga, M., and Gotoh, K. (2018). Formation of experience: the loss of human-nature interaction. *Front. Biol. Science* 14, 94–101. doi: 10.1002/fbs.1223.
- Krishnamoorthy, A., and Das, B. K. (2011). Vernacular architecture of India: an overview. *IAVQ e-Journal* 10, 435–448. Available online at: https://ojs.iaavq.com/pak0555_25-2_2010q_107-10.pdf.
- Korten, M. A. (2010). Across the threshold of India: Art, women, and culture. *Statistec, NY*. George S. Thompson.
- Kurita, M. (2018). The illustrated dictionary of Hindu iconography. Aldine Park, Abingdon, Oxon, New York, NY: Routledge. doi: 10.4153/9780429857899
- Survey of India. (n.d.). Available online at: <https://surveyofindia.gov.in/> (Accessed October 12, 2020).
- Kulkarni, T. T. (2016). *Nupur - the art of wood carving of traditional houses of Gujarat* in manuscript. Ahmedabad: Research Cell, School of Interior Design, CEET.
- Tipper, A., and Lal, A. (2012). *Vernacular traditions - contemporary architecture*. New Delhi, India: Energy and Environment House.
- Torres, J. N., and Samra, Z. (2014). Threshold spaces: The transitional areas between outside and inside in traditional Indian dwellings. *Heritage* 7, 6647–6711. doi: 10.1080/17445019.1233109
- Van Dijk, Scott, L. J. R. (2016). Visual methods in ethnography. *J. Geography* 116(4), 719–728. doi: 10.1177/0013264116660072
- Varley, R., and Kumar, R. (1995). In *Prakriti: The integral vision: The agency tradition and the arts of K. Varley* (Delhi, DK: Prithvi).
- Varley, R., and Soodan, R. (1993). In *Prakriti: The integral vision: Art in nature*, ed. R. Soodan (Delhi: DK, Prithvi).
- Vishnueghat, V. (2014). Redefining the geography of sustainability transitions by consolidating human-nature connections in rural areas. *Palgrave Comm. Soc. Policy* 11, 109031. doi: 10.1016/j.psc.2014.109031
- Vyas, S. V., and Joshi, A. J. (2014). Determination and discrimination in characteristics of coastal habitats in some parts of Bhadr region for. *Leif. Mar. Sci.* 39, 41–49. doi: 10.54431/lp-5795q7
- Vyas, S. V., and Joshi, A. J. (2013). Quantitative study of coastal flora of Bhadr region in Gujarat for. *J. Sci. Res.* 4, 337–341.
- Wahab, Z., Behre, J., and Wemmer, C. (2021). Towards a relational paradigm in sustainability: research, practice, and education. *Ecobio* 30, 74–84. doi: 10.1017/et.2020.225-01222
- Woo, J., Hazler, J. L., Williamson, E., and Wernick, S. (2018). A relational turn in sustainability science? Relational thinking, knowledge praxis and transformation. *Environ. People* 18, 304–325. doi: 10.1080/23750166.2018.1494417
- Yadav, P., Sami, U., and Gern, R. (2015). Studies on traditional heritage in Shikharwani Harala and wall painting: creative design. *Int. J. Res. Art Design* 1, 28–37.
- Yat, R. K. (2010). *Case study research: Design and methods*, 3rd Edn. Thousand Oaks, CA: Sage Publications.
- Zakaria, N. Z., Akmal, S., and Amin, A. E. (2014). Analysis of the end-user responses towards biophilic design implementation in Malaysian private hospitals. *Plant. Malaysia* 22, 640–650. doi: 10.21857/pm.v22n4.1459
- Zingales, de Baat, M. E. (2020). "The social-ecological design approaches to engineering sustainability" in Cities and nature (Cham: Springer International Publishing), 61–88.



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A coupled model for public health risk: hazard and urban vulnerability in 18 cities in Sichuan, China

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Introduction: In the research and practice of disaster prevention/mitigation and urban resilience development, although existing studies have conducted multidimensional assessments of urban vulnerability to hazards and infectious disease risks, limitations persist—such as the lack of bidirectional coupling mechanism analysis and a disconnection from planning implementation. These constraints hinder the systematic governance of public health risks and the advancement of resilient city development.

Method: This study selects 18 prefecture-level cities in Sichuan Province as case studies. By employing the entropy method and coupling coordination degree (CCD) model, we construct a “hazard–vulnerability” risk coupling model to systematically analyze the coupling coordination mechanisms, identify key influencing factors, and propose optimization pathways.

Results: (1) The coupling coordination degree (CCD) between infectious disease hazards and urban vulnerability in Sichuan Province remains at a relatively low level overall (mean = 0.384). Specifically, Chengdu demonstrates a “low vulnerability–high hazard” characteristic (0.031), while Guangyuan and Panzhihua exhibit optimal coordination states (0.655 and 0.649, respectively). (2) The region generally follows the distribution pattern where lower CCD corresponds to higher risk levels. The coordinated development types show dispersed spatial distribution, whereas recession-maladjusted types are predominantly concentrated in the Chengdu Plain and southern Sichuan regions. (3) Among CCD subtypes, the “hazard–deficit” type emerges as the dominant pattern. (4) Economic–spatial–social–environmental factors demonstrate not only significant interaction effects but also pronounced spatial heterogeneity characteristics.

Conclusion: Based on spatial coupling theory, this study innovatively constructs a “hazard–vulnerability” risk coupling model, which expands traditional risk assessment and urban vulnerability evaluation theories, providing a novel research perspective for urban risk management and regional sustainable development. The research results offer important quantitative evidence for formulating regionally differentiated public health strategies.

KEYWORDS

public health emergencies, risk coupling model, infectious disease hazards, urban vulnerability, entropy method, coupling coordination degree (CCD) model

1 Introduction

Public health emergencies, as global crises, have seen their impact mechanisms and spatial distribution characteristics become a cutting-edge research topic in interdisciplinary studies. From a historical perspective, from the Plague of Justinian to the COVID-19 pandemic, such events have not only caused significant casualties and economic losses (1, 2), but have also reshaped urban development trajectories through complex spatial interaction mechanisms (3). In contemporary urbanization processes, the concentration of factors and flow networks have simultaneously improved the efficiency of medical resource allocation while significantly increasing pathogen transmission risks (4). Therefore, it is essential to establish a scientific risk assessment framework to effectively implement urban planning strategies, public health policies, and emergency management measures.

In the field of infectious disease transmission mechanisms, significant academic progress has been achieved. Dai et al. systematically demonstrated the potential risks of respiratory disease transmission via aerosols in high-density urban environments (5), while Ruiz-Herrera et al. mathematically quantified the critical role of population mobility in epidemic spread (6). Notably, however, these studies primarily focus on the transmission dynamics of pathogens themselves, failing to adequately account for the regulatory effects of urban complex systems on transmission processes.

Meanwhile, urban vulnerability studies have thoroughly examined the impact of socioeconomic factors on public health emergency response capabilities (7), explicitly identifying spatial elements as key variables influencing disease transmission. These studies reveal how urban-rural spatial organization patterns critically determine epidemic prevention efficacy (8). Particularly noteworthy is Hahayri et al.'s research demonstrating how disparities in urbanization levels and regional development imbalances exacerbate health vulnerabilities, leading to spatial mismatches between public health service provision and disease burdens (9). However, these studies generally overlook pathogen-specific transmission routes and pathogenic mechanisms. Such disciplinary fragmentation has resulted in significant theoretical limitations and practical blind spots in existing risk assessment frameworks.

Existing studies have also revealed that the impact of urbanization on infectious disease transmission exhibits significant regional heterogeneity (10). This spatial variation manifests not only in the geographical disparities of transmission risks, but also triggers multi-level cascading effects within urban systems through the shockwaves of public health emergencies. Specifically, public health crises have both intensified the polarization of pre-existing patterns in disease transmission and socioeconomic spatial differentiation (11), while simultaneously giving rise to new vulnerability dimensions such as disparities in spatial accessibility, environmental justice imbalances, and inequitable health resource allocation (12). The spatial coupling and synergistic effects of these multidimensional inequities not only exacerbate the degree of risk heterogeneity in urban systems, but also pose systemic challenges to conventional public health risk management paradigms.

Building upon these research findings, scholars have begun to re-examine the adaptability of traditional urbanization models and advocate for establishing systematic, multi-tiered, and dynamically evolving urban resilience frameworks (13). Grounded in urban political ecology theory, Gaudy developed the "Zoonotic City" analytical framework, emphasizing that urbanization processes must be integrated with epidemiological characteristics to fully capture the complex interactions between health threats and environmental changes (14). Furthermore, Yang et al.'s empirical study in Hubei Province proposed that post-pandemic urban development should transcend mere economic agglomeration and scale expansion, shifting toward a new model prioritizing public service enhancement and amenity optimization (15). Additionally, Pacheco et al.'s systematic review demonstrated that increasing accessible public spaces and optimizing their adaptive use during health crises are emerging as critical innovations in urban design (16). These research advances provide vital theoretical foundations and practical pathways for constructing more resilient urban systems.

Through an in-depth analysis of current research advancements, three critical theoretical gaps remain to be addressed in the study of interactions between infectious diseases and urban systems. First, existing research paradigms are predominantly limited to unidirectional linear analyses, focusing either on the mechanisms of disease transmission and the impact of epidemics on urban systems, or examining the influence of urban factors on disease spread in isolation (17). This fragmented research perspective has led to insufficient understanding of the complex interaction mechanisms between hazards and vulnerabilities. Second, at the methodological level, current risk assessment frameworks lack adequate capacity to analyze the formation mechanisms of micro-scale risk heterogeneity within cities, making it difficult to effectively identify key drivers of risk differentiation across different regions (18). More crucially, despite substantial evidence demonstrating significant correlations between spatial organization patterns and epidemic control effectiveness, there remains a lack of integrated frameworks to effectively translate risk assessment results into urban planning intervention measures (19). These theoretical and methodological limitations urgently call for establishing systematic, multidimensional, and dynamic infectious disease risk assessment systems, and implementing precise interventions through scientific risk management approaches (20).

In summary, this study systematically conducted public health emergency risk assessment research using 16 prefecture-level cities in Jichuan Province as case studies. Methodologically, we first constructed comprehensive evaluation index systems for both hazard and urban vulnerability, employing the entropy method to determine indicator weights, subsequently measuring their index levels and analyzing spatial distribution characteristics. Building upon this foundation, the integrated risk assessment model quantified disaster risk levels and generated risk maps, verifying the effectiveness of the index system as an informative indicator for actual cumulative infection data (as the level of risk alone can be an informative indicator for all such issues). Furthermore, the CCD model was applied to analyze the spatial coupling relationship

TABLE 1. Classification of city size levels in various economic regions of Sichuan Province.

Economic zones	Hierarchical scale	City names	Current situation
Chengdu Plain	Megacity	Chengdu	The Chengdu Plain Economic Zone contains more than 50% of the province's permanent population, representing the most developed, densely populated, and industrially concentrated region in Sichuan. It ranks among the most influential and economically agglomerated areas in Western China.
	Type II large city	Mianyang	
	Medium-sized city	Deyang, Suining, Leshan, and Meichuan	
	Type I small city	Dazhou and Yibin	
Northwestern Sichuan	Type II large city	Nanchong	The Northwestern Sichuan Economic Zone exhibits relatively underdeveloped economic conditions. Urban settlements across all hierarchical scales remain undiversified, with regional centers Nanchong and Dazhou demonstrating limited radiating capacity. Certain towns and counties with large population outflow exist. The urbanization process lags behind provincial averages, constrained by infrastructure deficits and public service inadequacies.
	Medium-sized city	Daxue	
	Type I small city	Guangyuan, Guang'an, and Baichang	
Southern Sichuan	Type II large city	Yibin	The Southern Sichuan Economic Zone ranks second in provincial economic output. However, its core cities suffer from insufficient scale and weak agglomeration capacity, coupled with notable population outflow. The region also faces overlapping subdivisions in core industries and public service provision.
	Medium-sized city	Ziyang, Luzhou, and Neijiang	
Panxi	Medium-sized city	Nanchuan	The Panxi Economic Zone is currently the sole state-approved operational iron and steel base with the theme of comprehensive economic development and utilization. It boasts both resident population and regional GDP rankings fourth among the five major economic zones in Sichuan Province, reflecting a relatively lagging overall development level.

between hazards and vulnerability, not only classifying coupling combination types but also identifying key risk drivers for each category. Ultimately, empirical analysis based on pandemic infection growth data validated the reliability of the coupled risk assessment results. By developing the “hazard–vulnerability” risk coupling model, this study expands traditional risk assessment theory and provides scientific support for formulating effective risk management measures and urban planning strategies (34). The research holds significant theoretical and practical value for integrated disaster prevention and mitigation system planning, resilient city construction, and sustainable development.

2 Materials and methods

2.1 Study area and data sources

2.1.1 Study area

Sichuan Province, located in southwestern China, plays a pivotal role in major national strategies such as the Western Development Program, poverty alleviation initiatives, and the Chengdu–Chongqing Economic Circle development. Despite its well-developed transportation network that facilitates efficient population mobility and material flows, the urban system remains incomplete. Except Chengdu, the province lacks other megacities and Type I large cities, and has only three Type II large cities, resulting in population shrinkage among small-medium cities and excessive concentration in central urban areas. Although Sichuan ranks fifth nationally in regional GDP, its economic development shows significant spatial disparities. The overall development level remains relatively lagging, with pronounced urban–rural gaps, uneven resource allocation, and low spatial safety resilience. Historically prone to earth quakes and epidemics, the province's health risks have been further exposed during recent major pandemic outbreaks.

This study examines 18 prefecture-level and higher cities within four major economic zones of Sichuan (Table 1, Figure 1). The provincial capital Chengdu, with an urban population of 13.54 million, ranks as China's fifth megacity. Its rapid economic development has created significant population siphon effects, with its massive urban population far exceeding other cities in the province. The province's urban system comprises three Type II large cities (Mianyang, Nanchong, and Yibin), nine medium-sized cities (Luzhou, Daxue, Ziyang, Suining, Leshan, Meichuan, Panzhihua, Deyang, and Neijiang), and five Type I small cities (Guangyuan, Baichang, Ziyang, Guang'an, and Yulin), collectively constituting a hierarchical urban network beneath Chengdu's megacity dominance.

2.1.2 Data sources

This study uses both statistical data and web-based data. The statistical data used in this study were primarily sourced from the *Sichuan Statistical Yearbook 2023* (SSYB), *Sichuan Transportation Yearbook 2023* (STYB), municipal statistical yearbooks of individual cities (MSYB), and human resources and social security bulletins published by prefecture-level cities (MSHB). Data on licensed (assistant) physicians and hospital beds were mainly obtained from the *Sichuan Health Statistical Yearbook 2023* (SHSYB), while demographic indicators such as the proportion of population aged 65 and above (2020 data) were collected from the *Sichuan Population Census Yearbook 2020* (SPCY).

The infectious disease data pertain to the COVID-19 epidemic and was sourced from the official website of the Sichuan Provincial Health Commission.¹ The dataset includes confirmed cases reported at the prefecture-level city scale, covering the period from January 1, 2020, to December 31, 2022.

¹ <http://www.sc.gov.cn/>



FIGURE 1
The location of Sichuan Province

TABLE 2 Data sources

Data type	Resolution	Time range	Data sources
National postcode data	Year	2022	https://www.gov.cn/jiayuan/2022/04/20/content_5684444.htm
Point of Interest (POI) data	Year	2022	https://lbs.amap.com/
Epidemic statistics data	Daily	January 3, 2020–December 31, 2022	https://covid19.gov.cn/
Administrative domain boundary data			https://www.tianditu.gov.cn/

The network data consists of Point of Interest (POI) data for prefecture-level cities in Sichuan Province in 2022, obtained from Amap (Amap POI² [23]). This dataset includes the quantities of daily service facilities such as convenience stores, supermarkets, shopping malls, and restaurants, which are used to measure the density of living service venues. Additionally, the administrative boundary sector maps for each city were acquired from the National Platform for Geospatial Information Services.³ Table 2 summarizes the relevant data information, including data types, temporal resolution, time range, and data sources.

2.2 Infectious disease disasters comprehensive risk assessment index system

To comprehensively understand integrated disaster risk, international organizations such as the United Nations Office for Disaster Risk Reduction (UNDRR) and the United Nations Development Programme (UNDP) have incorporated disaster risk reduction measures into national planning and decision-making processes based on metric frameworks [24]. The discourse on Disaster Risk Reduction (DRR) is undergoing a paradigm shift toward vulnerability-oriented approaches, with vulnerability emerging as a common evaluative characteristic in numerous risk assessments,

providing practical information for accurate disaster prevention and mitigation [24].

Scholars have conducted in-depth research on integrated risks of infectious disease disasters. For instance, Mete et al. employed three risk factors from the INFORM COVID-19 Risk Index—hazard and exposure, lack of coping capacity, and vulnerability—to reassess national disaster risks in two phases [25]. Pang et al. developed a disaster loss index model based on vector vulnerability, disaster-prone environmental instability, hazard (severity), disaster prevention capacity, and emergency response capability to study pandemic transmission's environmental risks and socioeconomic impacts [26]. Pluchino et al. established a risk index framework incorporating disease hazard (H), regional exposure (E), and population vulnerability (V) to assess epidemiological risks across geographical areas and identify high-risk zones [27]. Katagi et al. created an integrated risk assessment framework combining hazard and vulnerability, defining infectious disease risk as $C \sim H \times V$, followed by risk assessment and mapping [28]. In summary, risk index evaluations primarily focus on disease risk, hazards, and vulnerability. By comprehensively considering multiple risk factors and their impacts, more effective risk assessment and management can be achieved. When constructing the comprehensive risk assessment index system for infectious disease disasters in this study, it becomes necessary to redefine these two subcategories—hazard and vulnerability.

The transmission intensity of infectious diseases determines both the likelihood of disease occurrence and the extent of its spread, necessitating the selection of indicators that can characterize disease transmission patterns as hazard factors. Analysis of viral epidemiological characteristics [29, 30] reveals that transmission routes primarily include aerosol transmission, airborne transmission,

² <https://lbs.amap.com/>

³ <https://www.tianditu.gov.cn/>

and direct contact transmission, with influencing factors being highly complex (33). The emergence and spread of infectious diseases are associated with several determinants, encompassing both anthropogenic factors (e.g., population density, travel and trade patterns, susceptibility across different demographic groups) and ecological factors (32). Therefore, this study extracts hazard-related influencing factors from the following dimensions: population characteristics (33), population aggregation (34), demographic dynamics (35), and environmental factors (36). These elements collectively form the framework for constructing the indicator system.

Epidemic disasters differ from natural disasters in that they primarily affect human health through interpersonal transmission and lead to lasting socioeconomic consequences. As a result, pandemic risk assessment studies tend to focus more on the vulnerability of populations and socioeconomic systems while often neglecting spatial considerations. However, many drivers of pandemic vulnerability are inherently linked to global connectivity and urbanization levels, arising from the complex interplay of spatial structural imbalances, uneven economic development, and insufficient governance capacity. Any deterioration in these factors may increase a city's vulnerability and risk (37). In this study, we define vulnerability as the sensitivity of urban systems to external disturbances and their lack of coping capacity, which makes their structure and function prone to change.

To construct an urban vulnerability indicator system for public health emergencies, we conducted a comprehensive review of relevant literature, including the Population Vulnerability Index widely used in public health and medical fields (38), the Social Vulnerability Index (SVI) (39), urban vulnerability assessments (UVA) that incorporate both social and physical factors in local planning (40), and the Pandemic Vulnerability Index (PVI) (17). We extracted key influencing factors on urban vulnerability from socioeconomic (41), spatial-environmental (42), and infrastructural dimensions (43) to build our indicator system.

The establishment of a risk coupling assessment model for infectious disease hazards and urban vulnerability can effectively measure the threat level of infectious diseases and the degree of urban vulnerability, identify risk-influencing factors, and subsequently formulate targeted epidemic prevention and urban planning strategies. This provides crucial scientific support for disaster prevention and mitigation as well as resilient city development. To explore potential variables influencing infectious disease hazards and urban vulnerability, this study referenced variables included in previous research. Based on principles of data relevance, availability, and reliability, we screened and categorized key indicators to construct a comprehensive integrated risk assessment framework (Table 1).

2.3 Data standardization

In a multi-indicator evaluation system, different indicators may have varying units of measurement. Therefore, data standardization is required during the evaluation process. There are two types of evaluation indicators: positive and negative. For positive indicators, higher values indicate greater risk and vulnerability; for negative indicators, higher values indicate lower risk and vulnerability. Consequently, this study employs the extremum method to conduct positive transformation of all original indicators (Equations 1–2).

Positive indicators:

$$X_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (1)$$

Negative indicators:

$$X_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (2)$$

Where x_{ij} is the original data of the evaluation index; x_{\max} and x_{\min} are the maximum and minimum values of the evaluation index; X_{ij} is the indicator value after standardized processing. Here, i refers to the prefecture-level and above cities in the study, totaling $m = 10$. j represents the various indicators.

2.4 Entropy method

The entropy method objectively determines indicator weights by measuring information entropy to quantify data variability, effectively eliminating biases inherent in subjective weighting approaches (44). In information theory, entropy serves as a metric for system disorder and the amount of useful information contained within datasets. When evaluation objects demonstrate significant disparities in specific indicators, lower entropy values indicate greater informational utility, warranting higher weight assignments (45). The methodological procedure involves standardizing raw data, calculating information entropy for each indicator, and deriving weight coefficients based on entropy values (46). This process equitably accounts for relative importance among indicators, ensuring scientifically robust weight allocation. For public health risk assessment, the entropy method proves particularly effective in handling multi-source heterogeneous data, precisely capturing each risk factor's actual contribution to support comprehensive evaluations (Equations 3–7).

The feature proportion of the i -th city under the j -th indicator can be defined as follows:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}} \quad (3)$$

Where m represents the total number of prefecture-level and above cities (here, $m = 10$), and the calculation constant k is given by:

$$k = \frac{1}{\ln(m)} \quad (4)$$

The Information entropy of the j -th indicator can be defined as follows:

$$e_j = -k \sum_{i=1}^m P_{ij} \ln(P_{ij}) \quad (5)$$

TABLE 1 Comprehensive risk assessment indicator system for urban infectious disease disasters

Target	Sub-system	Dimension	Indicator	Definition	Source	Direction	Weight
Comprehensive risk	Infectious disease based	Population characteristics	Proportion of population aged 65 and over (X11)	Percentage of permanent residents aged ≥ 65 years in the region (%)	TPCY 2010	+	0.016
			Population living in poverty (X12)	Percentage of population receiving minimum living allowance (%)	ADVR2011	+	0.001
		Population aggregation	Population Density (X13)	Permanent residents per unit land area (persons/km ²)	SYVB 2014	+	0.145
			Employment Density (X14)	Total employed persons per built-up area (10,000 persons/km ²)	MSVB2011	+	0.002
		Demographic dynamics	Immigrant (inward) arrivals (X15)	Annual domestic tourist arrivals (10,000 persons)	SYVB 2014	+	0.231
			Public transport vehicles per 10,000 population (X16)	Number of operational public buses/taxis (urban districts) per 10,000 permanent residents (10,000 persons)	SYVB 2014	+	0.144
			Highway passenger traffic volume (X17)	Annual highway passenger transport volume (10,000 persons)	ETTR 2011	+	0.126
		Environmental factors	PM _{2.5} concentration (X18)	Annual mean 24-hourly index (µg/m ³)	DEEB1013	+	0.075
			Relative humidity (X19)	Annual mean relative humidity (%)	SYVB 2014	+	0.328
			Mean air temperature (X20)	Annual mean air temperature (°C)	SYVB 2014	-	0.038
	Urban vulnerability	Spatial vulnerability	Residential density (X21)	Per capita housing floor area (m ² /person)	SYVB 2013	-	0.125
			Alleyway density (X22)	Number of courtyards/alleys/vegetation/shopping malls per km ² (based on POI data)	Amqp POI	+	0.072
			Transport facility density (X23)	Number of bus stops per km ² (based on POI data)	Amqp POI	+	0.200
			Green coverage rate (X24)	Percentage of green space in built-up area (%)	SYVB 2013	-	0.014
		Economic vulnerability	Open space density (X25)	Number of parks/public squares per km ²	SYVB 2013	-	0.011
			Unemployment rate (X26)	Registered urban unemployment rate (%)	MSYB2011	+	0.002
			Income per capita (X27)	Annual per capita disposable income of residents (10,000 CNY)	SYVB 2013	-	0.012
			Health expenditure as percentage of GDP (X28)	Government health expenditure as percentage of GDP (%)	HHVB 2013	-	0.048
			Annual per capita household savings deposit balance (X29)	Per capita savings deposits of urban/rural residents (10,000 CNY)	SYVB 2013	-	0.040
			Emergency supplies reserve expenditure as a percentage of GDP (X30)	Government emergency reserves expenditure as percentage of GDP (%)	SYVB 2013	-	0.047
		Social vulnerability	Physicians per 10,000 people (X31)	Licensed (contract) physicians per 10,000 permanent residents	HHVB 2013	-	0.000
			Hospital beds per 10,000 inhabitants (X32)	Number of hospital beds per 10,000 permanent residents	HHVB 2013	-	0.000
			Coverage rate of basic medical security schemes (X33)	Coverage rate of basic pension insurance (%)	ADVR2011	-	0.000

Calculate the divergence coefficient g_j for the j -th indicator:

$$g_j = 1 - e_j \quad (6)$$

Calculate the weight of the j -th indicator:

$$w_j = \frac{g_j}{\sum_{j=1}^n g_j} \quad (7)$$

2.5 Measure the disaster hazard index and urban vulnerability index

This study calculates the disaster hazard index by combining standardized indicator values with their respective weights, reflecting both the hazard intensity levels and spatial distribution patterns across the study areas. The computational formula is expressed as follows (Equation 8):

$$H_i = \sum_{j=1}^n W_j \times X_{ij} \quad (8)$$

Where H_i denotes the disaster hazard index for the i -th city, while higher values indicate greater hazard intensity. W_j represents the weight of the j -th indicator derived from the entropy method. X_{ij} corresponds to the standardized value of the indicator.

To quantify regional vulnerability, the same methodology was employed to calculate the urban vulnerability index, thereby enabling quantitative analysis of both the magnitude and spatial distribution of vulnerability across the study areas (Equation 9):

$$V_i = \sum_{j=1}^n W_j \times X_{ij} \quad (9)$$

Where V_i denotes the urban vulnerability index for the i -th city, while higher values indicate greater vulnerability degree. W_j represents the weight of the j -th indicator derived from the entropy method. X_{ij} corresponds to the standardized value of the indicator.

2.6 Calculation of composite risk index

Risk analysis should concurrently consider both infectious disease hazard and urban vulnerability, as risk is a function of hazard and vulnerability. The computational formula can be expressed as (38, 39) (Equation 10):

$$R_i = H_i \times V_i \quad (10)$$

The above calculation demonstrates that regional disaster risk escalates with increasing hazard intensity and vulnerability levels.

2.7 Coupling coordination degree model (CCDM)

The Coupling Coordination Degree Model (CCDM), based on coupling theory effectively evaluates interaction effects and coordinated development levels between different systems. It has been widely applied to examine relationships among social, economic, and ecological systems (96, 113), including production-living-ecological spaces (22, 37), economy-ecology interplay (34, 46), Urbanization-ecological environment dynamics (36), Cultural landscape conservation vs. socioeconomic development (37). Recently, CCDM has transitioned from social-economic-ecological studies to disaster risk research, enabling in-depth analyses of spatial coupling relationship between multidimensional poverty and the risk of geological disaster (38), the coupling relationship between flood risk and population vulnerability (39), integrated effects and multidimensional impacts of "Hazard-Exposure-Vulnerability" on urban flood risks (40). These studies demonstrate applicability of CCDM in disaster risk assessment frameworks. However, existing research lacks spatial coupling perspectives to unravel interaction mechanisms between acute public health hazards and urban vulnerability.

"Coupling" refers to the process of interaction and mutual influence between two or more elements (41). This study employs CCDM to analyse the interdependent or mutually constraining relationships between disaster hazards and urban vulnerability. Within CCDM research, most scholars adopt the conventional model structure, calculated as follows (Equations 11–13):

$$C = 2 \times \sqrt{\frac{H_i \times V_i}{(H_i + V_i)^2}} \quad (11)$$

$$T = \alpha H_i + \beta V_i \quad (12)$$

$$D = \sqrt{C \times T} \quad (13)$$

Given the dimensional differences between disaster hazards and urban vulnerability, normalized ordinal values were employed to calculate their synchronization and overall coordination degree (Equations 14–16). Based on the final coupling coordination degree (D) values, and referencing the classification framework from Xiang et al.'s study (34), the coordinated development status between disaster hazards and urban vulnerability was categorized into 4 major classes. These were further subdivided into 8 subtypes according to the proportional relationship between the two systems (Table 4):

$$C = \frac{T(x)^k + g(x)^k}{\{\alpha f(x) + \beta g(x)\}^{2k}} \quad (14)$$

$$T = \sqrt{\alpha f(x) + \beta g(x)} \quad (15)$$

$$D = \sqrt{C \times T} \quad (16)$$

TABLE 4 Classification of coupling coordination types between disaster hazard and urban vulnerability

Coupling coordination type	Coupling coordination degree	Classification rule	Relation/discrimination feature	Coupling coordination subtype
Coordinated development	$0.4 \leq D \leq 1$	$0 \leq H-V \leq 0.1$	Synchronized coordinated development	Synchronization development
		$H-V > 0.1$	Coordinated development with urban vulnerability lag	Coordinated-urban vulnerability lagging
		$V-H > 0.1$	Coordinated development with disaster hazard lag	Coordinated-disaster hazard lagging
Barely coordinated development	$0.1 \leq D < 0.4$	$0 \leq H-V \leq 0.1$	Synchronized barely coordinated development	Synchronization development
		$H-V > 0.1$	Barely coordinated development with urban vulnerability lag	Coordinated-urban vulnerability lagging
		$V-H > 0.1$	Barely coordinated development with disaster hazard lag	Coordinated-disaster hazard lagging
On the verge of disorder	$0.4 \leq D < 0.5$	$0 \leq H-V \leq 0.1$	Synchronized on the verge of disorder	Disorder of both hazards and vulnerability
		$H-V > 0.1$	On the verge of disorder development with urban vulnerability lag	Disorder-urban vulnerability lag
		$V-H > 0.1$	On the verge of disorder development with disaster hazard lag	Disorder-disaster hazard lag
Disorder and recession	$0 \leq D < 0.1$	$0 \leq H-V \leq 0.1$	Synchronized disorder and recession development	Disorder of both hazards and vulnerability
		$H-V > 0.1$	Disorder and recession development with urban vulnerability lag	Disorder-urban vulnerability lag
		$V-H > 0.1$	Disorder and recession development with disaster hazard lag	Disorder-disaster hazard lag

Where C is the coupling degree, T is the coordination index between disaster hazards and urban vulnerability, D is the coupling coordination degree, $f(x)$ is the normalized value of disaster hazards ranking, $g(x)$ is the normalized value of urban vulnerability ranking, k is an adjustment coefficient (typically $2 \leq k \leq 5$). To enhance discriminative capacity, this study sets $k = 3$ following Su et al. (62). Considering that $f(x)$ is as important as $g(x)$ (i.e., $\alpha + \beta = 1$, with $\alpha = \beta = 0.5$). The higher the value of D is, the better the coordination degree between disaster hazards and urban vulnerability is.

3 Results

3.1 Integrated measurement and spatial distribution of infectious disease hazard and urban vulnerability

The standardized indicators were objectively weighted using the entropy method, yielding the respective indicator weights for infectious disease hazards and urban vulnerability (Figure 2, 3) as well as dimensional indices (Table 1). This enabled quantitative measurement of infectious disease hazards, urban vulnerability, comprehensive risk, and coupling coordination degree, with regional distribution patterns visualized through spatial mapping techniques. Furthermore, the study conducted qualitative analysis by incorporating regional development characteristics specific to Sichuan Province.

3.1.1 Comprehensive measurements and spatial distribution of the infectious disease hazard

Through a comprehensive evaluation of population characteristics, population aggregation, population mobility, and environmental exposure, this study reveals the infectious disease risk levels and spatial distribution patterns across cities in Sichuan Province. The quantitative risk scores ranged from 0.149 to 0.761. Chengdu exhibited the highest risk index at 0.761, while all other cities scored below 0.5, indicating generally low-to-moderate risk levels. These findings demonstrate the significant effectiveness of Sichuan's regional epidemic prevention policies in risk management.

Furthermore, Table 2 and Figure 4 show that population mobility constitutes the most influential factor for infectious disease risk. The key contributing elements include domestic tourist numbers, public transportation vehicles per 10,000 people, population density, and highway passenger volume.

Using the Natural Breaks method in ArcGIS (63, 64), the hazard index was classified into five risk levels: extremely high, high, moderate, low, and very low (Figure 3). Spatially, the disaster risk across Sichuan Province exhibits distinct regional differentiation, closely correlated with urban scale, geo-economic factors, and natural environment.

The extremely high-risk zone is represented by the megacity Chengdu, where elevated risk likely stems from dense population, economic activities, and urban expansion-induced environmental disturbances. Medium-to-high risk zones include large and medium-sized cities such as Yibin, Luzhou, Deyuan, Meishan, and Zigong. In contrast, low and very low-risk areas are primarily distributed across smaller peripheral cities like Panshihua, Guangyuan, and Daxi.

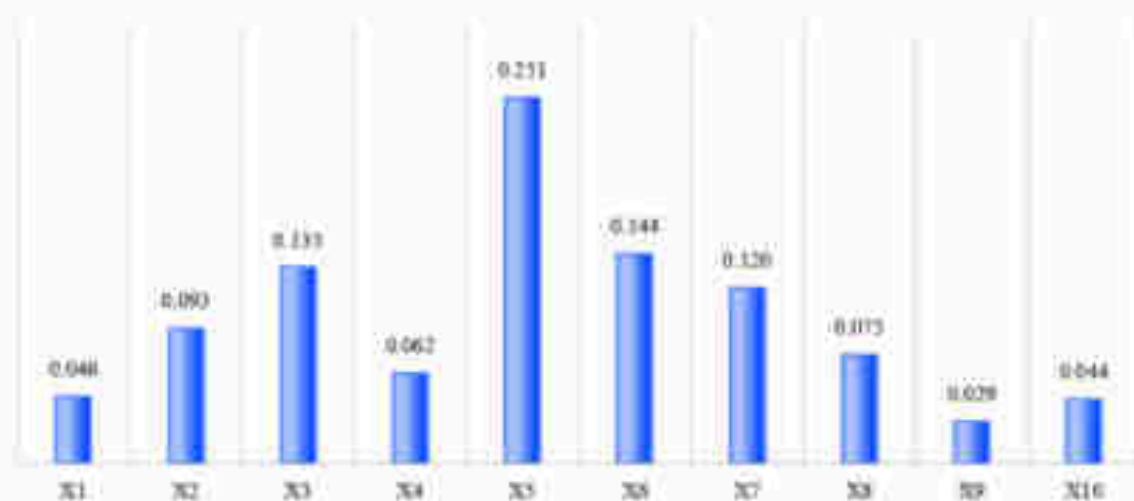
Weighting of Infections Disease Risk Indicators

FIGURE 2
Weight of infection disease risk indicators

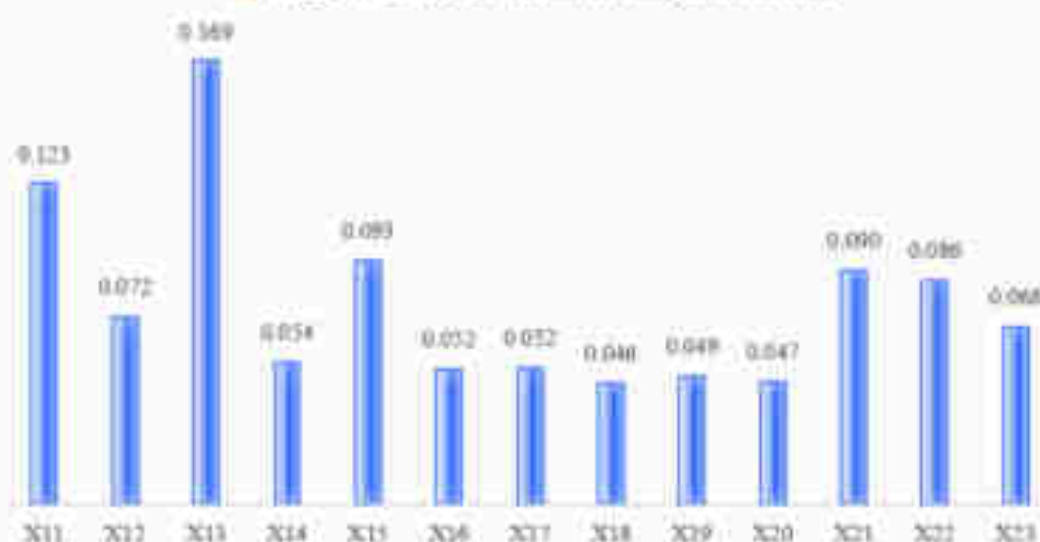
Weighting of Urban Vulnerability Indicators

FIGURE 3
Weight of urban vulnerability indicators

where abundant environmental resources and lower development intensity may contribute to risk mitigation.

Overall, this spatial risk pattern reflects both the constraints of natural geographical conditions and the impacts of regional development disparities.

3.1.2 Comprehensive measurements and spatial distribution of the urban vulnerability

The urban vulnerability index reflects a city system's sensitivity to internal and external disturbances and its lack of coping capacity—attributes that make its structure and function prone to change. Through a comprehensive evaluation of spatial layout, economic development,

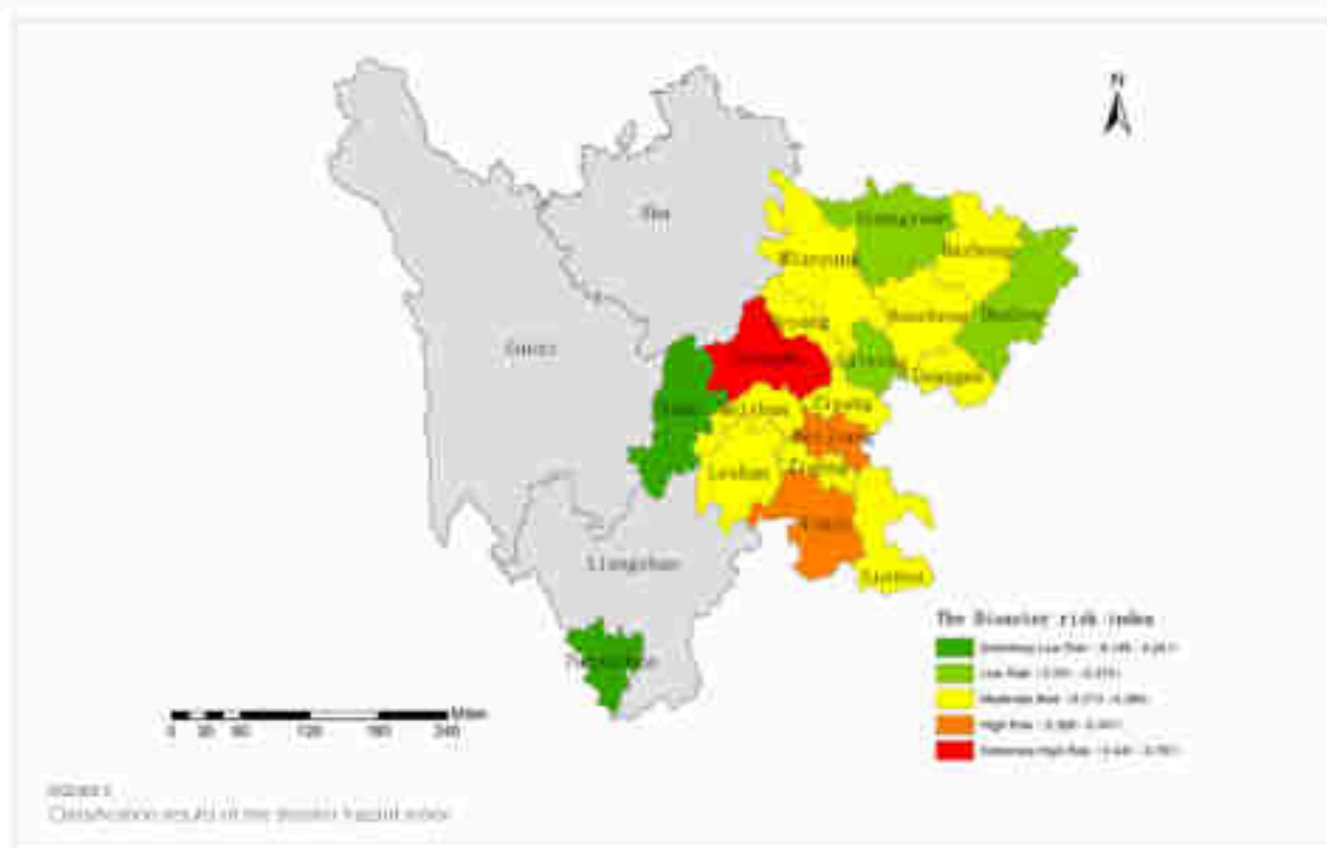
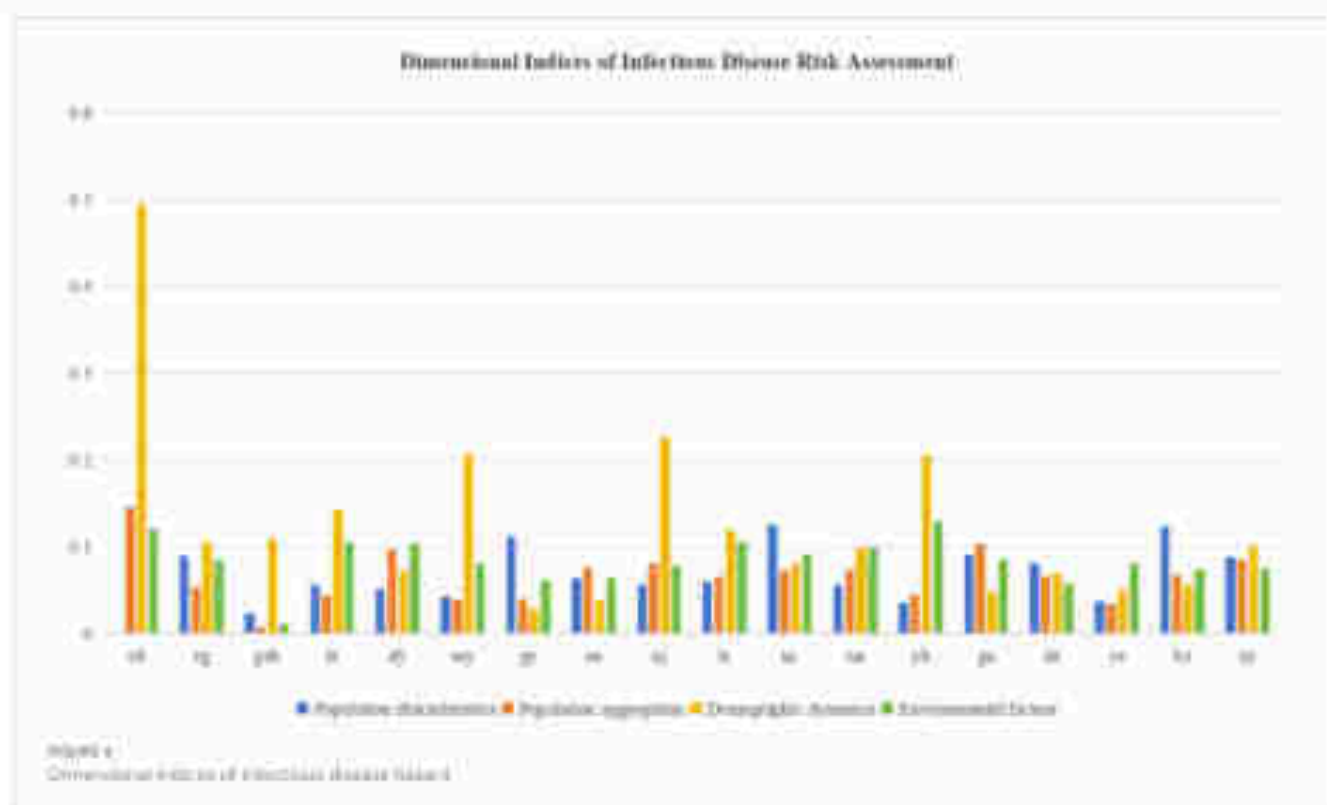
and social systems, this study reveals the vulnerability levels and spatial distribution characteristics across cities in Sichuan Province.

Quantitative vulnerability scores ranged from 0.383 to 0.720. Chengdu showed the lowest vulnerability index (0.383), followed by Nanchong (0.402), while most other cities scored above 0.5, indicating medium-to-high vulnerability levels. Meichuan exhibited the highest vulnerability index at 0.720. These results demonstrate the inherent vulnerability of urban systems in Sichuan when responding to public health emergencies.

As shown in Table 3 and Figure 4, spatial vulnerability demonstrated the most significant average influence. Key contributing factors included transportation facility density, residential density,

Table 2. Integrated risk assessment: sub-system components and dimensional reduction.

Codes	Population characteristics	Population aggregation	Demographic dynamics	Environmental factors	Infectious disease hazard	Spatial Vulnerability	Economic Vulnerability	Social Vulnerability	Urban Vulnerability	Comprehensive risk
cd	0.001	0.147	0.044	0.111	0.701	0.171	0.041	0.079	0.343	0.129
cg	0.089	0.054	0.103	0.084	0.552	0.162	0.123	0.082	0.415	0.158
ph	0.023	0.007	0.139	0.018	0.144	0.204	0.189	0.079	0.464	0.089
la	0.039	0.084	0.141	0.109	0.349	0.187	0.103	0.113	0.469	0.161
de	0.014	0.097	0.072	0.109	0.521	0.114	0.106	0.120	0.546	0.187
mc	0.045	0.040	0.207	0.080	0.564	0.151	0.140	0.120	0.553	0.197
gt	0.111	0.000	0.019	0.041	0.240	0.136	0.199	0.073	0.419	0.101
se	0.064	0.079	0.078	0.063	0.240	0.177	0.179	0.143	0.523	0.125
re	0.007	0.081	0.222	0.078	0.441	0.286	0.115	0.101	0.395	0.258
ls	0.016	0.066	0.114	0.005	0.351	0.161	0.183	0.114	0.546	0.197
te	0.120	0.072	0.061	0.081	0.369	0.076	0.189	0.119	0.412	0.148
mc	0.019	0.072	0.094	0.109	0.327	0.141	0.163	0.116	0.720	0.236
rh	0.010	0.045	0.200	0.129	0.414	0.210	0.111	0.116	0.566	0.154
ga	0.081	0.005	0.049	0.085	0.427	0.166	0.172	0.206	0.039	0.216
de	0.081	0.045	0.049	0.007	0.273	0.146	0.181	0.180	0.109	0.159
te	0.017	0.014	0.093	0.069	0.261	0.285	0.187	0.041	0.113	0.101
se	0.124	0.047	0.098	0.071	0.320	0.247	0.126	0.117	0.119	0.166
re	0.084	0.066	0.102	0.074	0.338	0.136	0.145	0.087	0.049	0.213



road network density, open space density, number of doctors, and hospital bed capacity. This reflects the close relationship between regional development levels and the balance of spatial configurations.

Using the Natural Breaks classification method in ArcGIS 10.8, the vulnerability index was categorized into five levels: extremely high, high, moderate, low, and extremely low vulnerability zones.

Figure 7 Spatially, urban vulnerability across Sichuan Province exhibits distinct regional differentiation.

The extremely low vulnerability zone is represented by the megacity Chengdu, whose resilience stems from advanced economic development and a comprehensive public service system. Cities like Nanchong and Zigong also demonstrate relatively low vulnerability due to their sound economic conditions, while Guangyuan benefits from stable geological environmental conditions.

Panzhihua and Luzhou fall into the low vulnerability category, with Mianyang and Suining classified as moderately vulnerable. High vulnerability areas such as Leshan, Yibin, and Guang'an may be influenced by multiple factors including geological disaster risks, industrial environmental pressures, and imbalanced public services.

Overall, this spatial pattern of urban vulnerability reflects both variations in natural geographical conditions and disparities in regional development levels.

3.2 Comparative analysis of composite risk mapping versus observed epidemic risk patterns

Based on the aforementioned assessment results of infectious disease hazards and urban vulnerability, we calculated the comprehensive risk index. Sichuan Province generally exhibits a low overall risk level. The provincial capital Chengdu showed the highest risk index (0.291), while Guangyuan and Panzhihua demonstrated the lowest values.

Using the Natural Breaks classification method in ArcGIS (43, 44), the study area was divided into five risk levels: low, relatively low, moderate, relatively high, and high risk zones, as illustrated in Figure 8. Spatially, the risk distribution across Sichuan follows a "high in central regions, low in peripheral areas" pattern. The

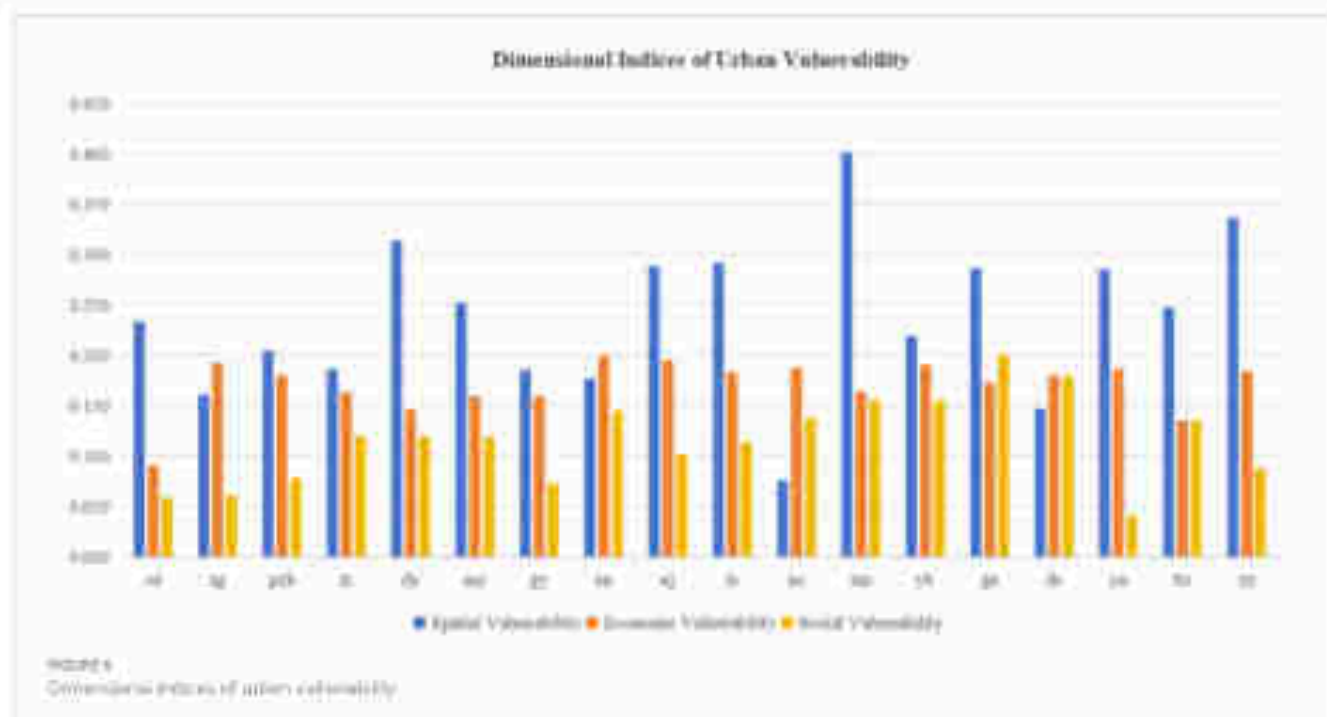
Chengdu Plain and southern Sichuan regions show significantly higher risk levels compared to Panxi and northeastern Sichuan areas.

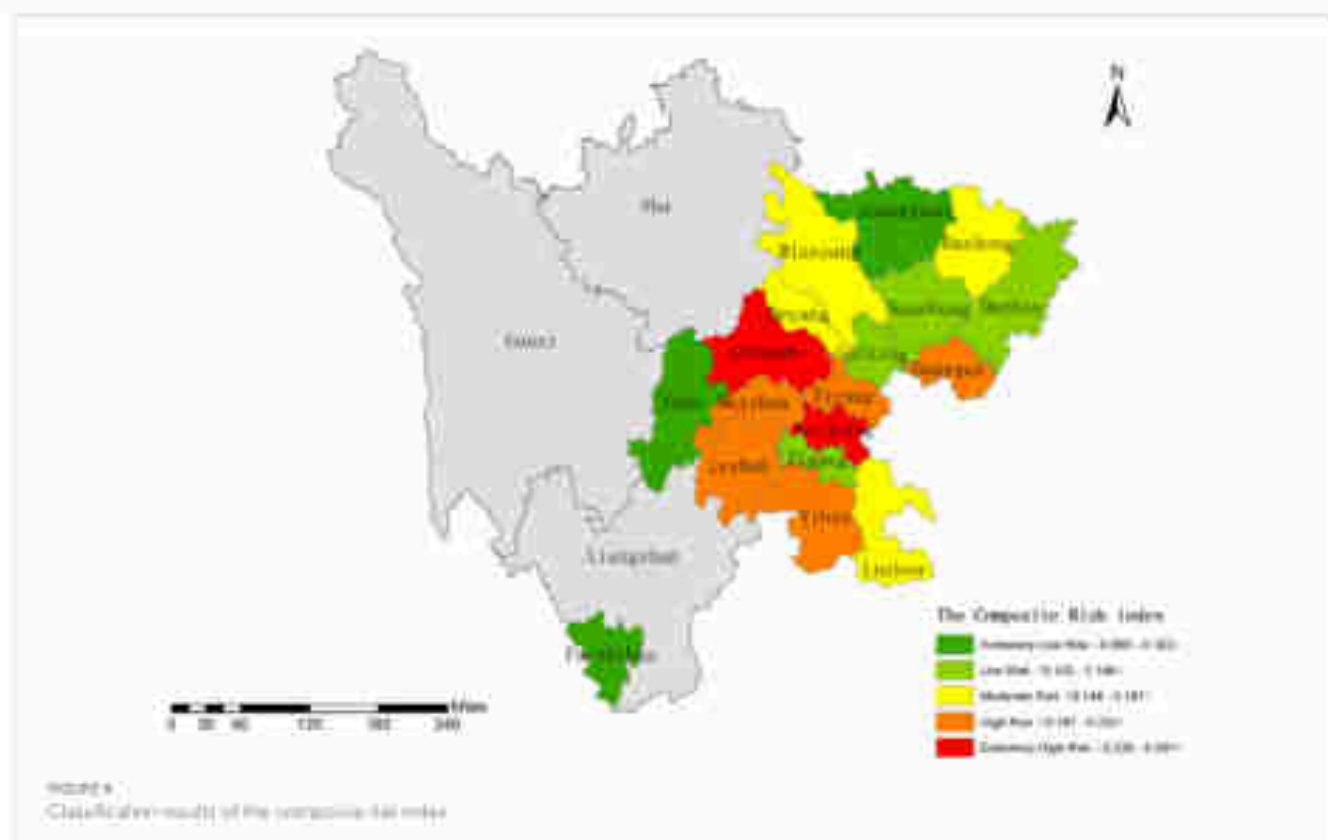
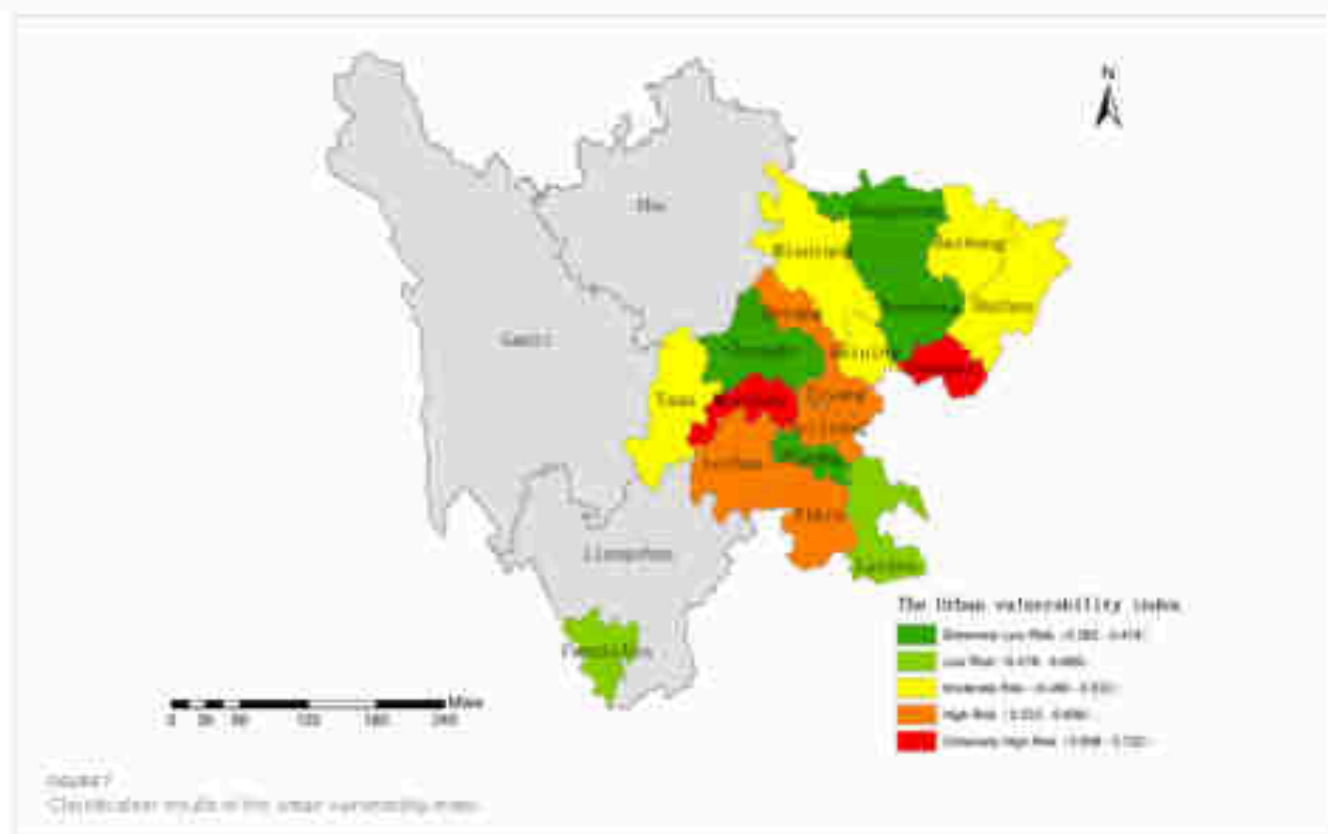
The Chengdu Plain and southern Sichuan concentrate most of the province's large and medium-sized cities. While these urban areas benefit from advanced economic development and well-established infrastructure, they simultaneously face challenges of high population density and strong mobility, leading to elevated infectious disease transmission risks. Notably, Chengdu presents a characteristic "low vulnerability-high risk" profile. In contrast, Panxi and northeastern Sichuan primarily consist of smaller cities or remote areas (e.g., Panzhihua, Guangyuan, and Ya'an), featuring lower population density, reduced human activity intensity, and higher natural environmental carrying capacity, resulting in comparatively lower comprehensive risk indices.

We conducted correlation analysis between the comprehensive risk index and actual cumulative infection cases to evaluate whether the risk indicator system could effectively reflect infection patterns (45). Spearman's rank correlation analysis (Table 4) revealed a statistically significant positive correlation between the two variables ($r_s = 0.680$, $p = 0.002$) at the 0.01 significance level. These results demonstrate that increased comprehensive risk index significantly correlates with higher cumulative infection numbers, and the geographical distribution characteristics of the risk index effectively mirror the spatial distribution patterns of actual case numbers.

3.3 Measurement results and spatial characteristics of CCD

This study calculated the Coupling Coordination Degree (CCD) index to examine the interaction and coordination between infectious disease hazards and urban vulnerability. The overall CCD level across





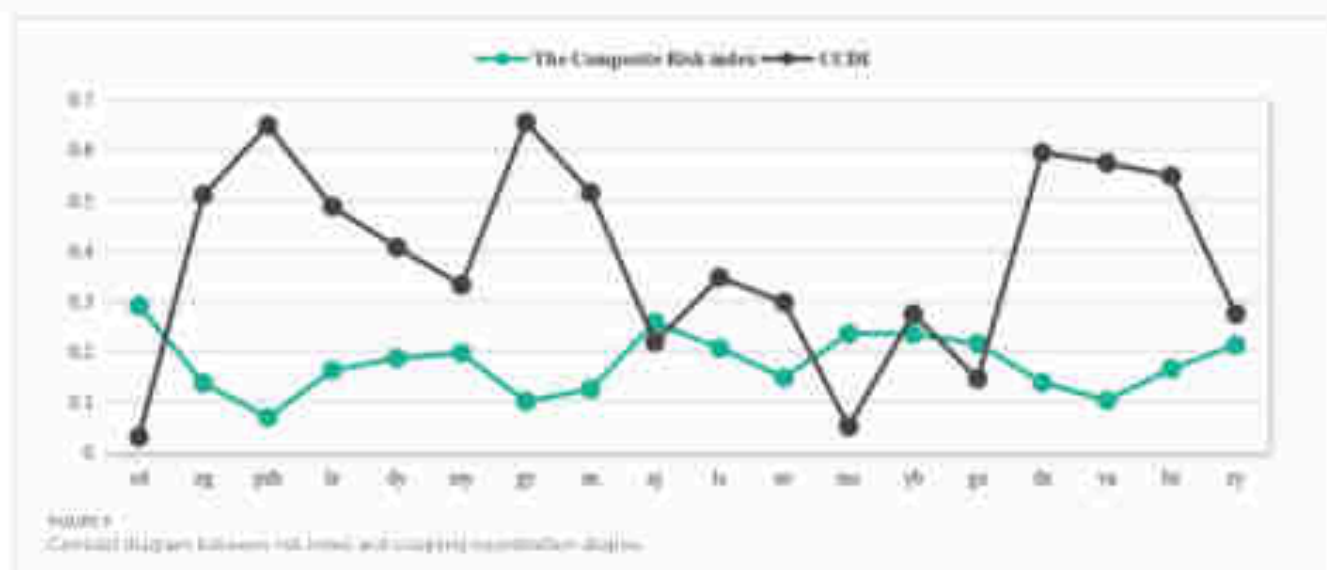
the study area was relatively low (mean = 0.384). Guangyuan and Panzhihua showed the highest CCD values (0.655 and 0.649, respectively), while Chengdu had the lowest CCD (0.031). As a

megacity, Chengdu exhibited extremely low urban vulnerability but exceptionally high infectious disease risk, resulting in severe coupling coordination imbalance.

TABLE 8 Spearman's rank correlation analysis.

Type of variable	The composite risk index	Correlation		The composite risk index	Actual cumulative case counts
		Correlation coefficient	Significance (two-tailed)		
Type of variable	The composite risk index	r	0.000**	0.000**	0.000**
		N	18	18	18
	Actual cumulative case counts	Correlation coefficient	0.000**	0.000**	0.000**
		Significance (two-tailed)	0.000**	0.000**	0.000**
		N	18	18	18

** The correlation is statistically significant at the 0.01 level (two-tailed).



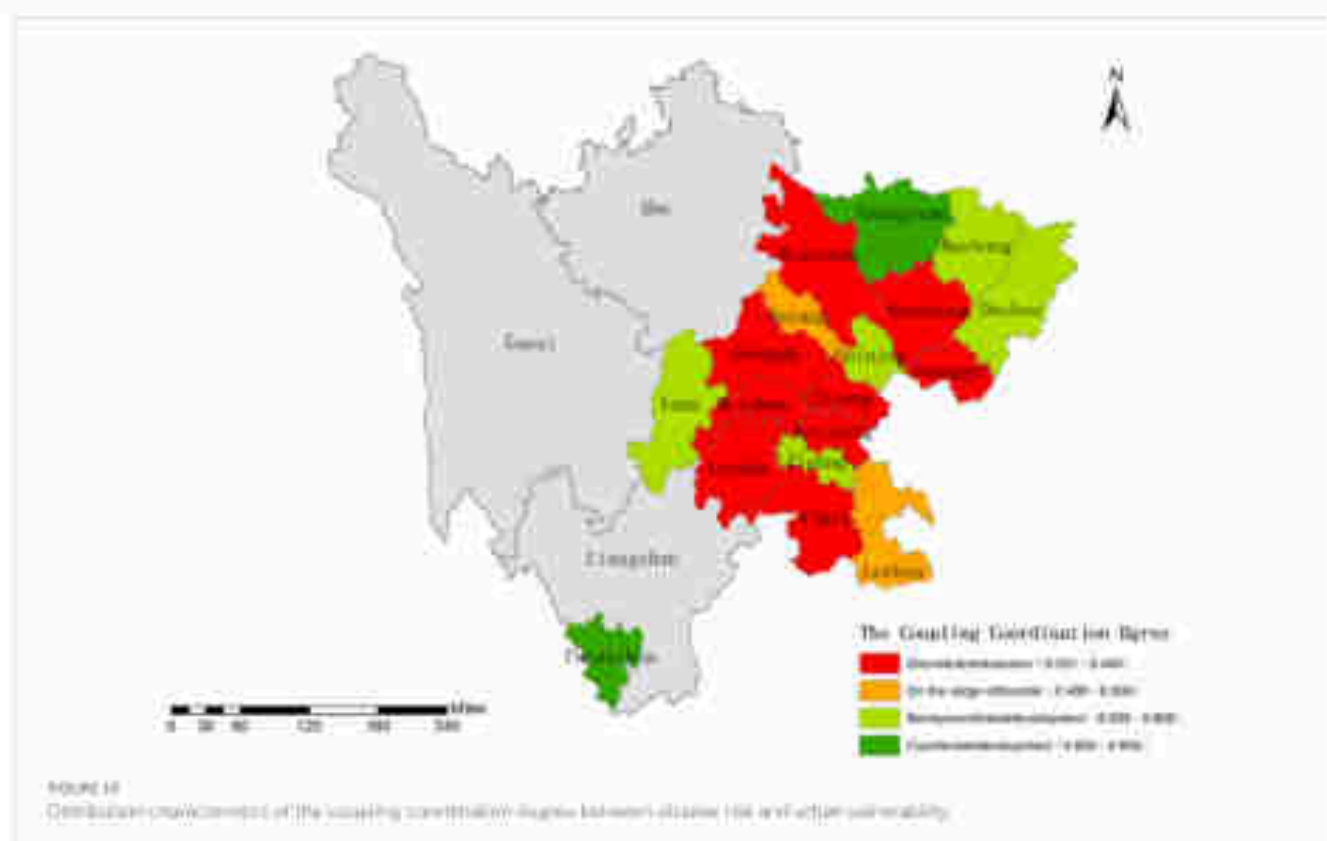
Based on the CCD model established in Section 2.7, we classified the study area into four coordination types using the following thresholds: coordinated development ($0.6 \leq D \leq 1$), marginal coordination ($0.5 \leq D < 0.6$), near imbalance ($0.4 \leq D < 0.5$), and declined imbalance ($0 \leq D < 0.4$). Figure 9 reveals a spatial pattern where "lower CCD corresponds to higher risk." Coordinated development cities were spatially dispersed, whereas declined imbalance cities were predominantly concentrated in the Chengdu Plain and southern Sichuan regions (Figure 10).

In-depth analysis reveals that the "hazard-dominant lagging" pattern predominates in the coupling coordination types across Sichuan Province. Cities achieving coordinated or marginally coordinated development, such as Fanchi, Ziyang, and Guangyuan, have made preliminary progress in aligning risk governance with spatial planning. Within the disordered and declined coordination categories, the regional risk patterns exhibit significant spatial heterogeneity. Chengdu demonstrates a characteristic "imbalanced/vulnerability lagging" type, while other cities predominantly follow an "imbalanced/hazard lagging" pattern. Empirical evidence confirms a notable positive feedback effect between urban vulnerability levels and infectious disease hazards, where heightened vulnerability not only exacerbates epidemic transmission risks by weakening systemic resilience but also perpetuates coupling system imbalances.

The aforementioned research reveals that the core mechanism influencing coupled coordinated development stems from multidimensional interactions among economic-spatial-social-environmental systems. This manifests in two distinct patterns: In rapidly developing regions (e.g., Chengdu, Mianyang), economic growth leads to excessive factor concentration, forming a "high investment-high density-high risk" transmission chain; whereas in underdeveloped areas (e.g., Guang'an), insufficient development momentum creates a vicious cycle of "low input-low protection-high vulnerability." These findings align with the "economic foundation-spatial structure-governance capacity" synergistic mechanism proposed in Shalhar et al. (33), unveiling the coupled pathways of regional system complexity.

First, the economic-spatial coupling in the Chengdu Plain region demonstrates a significant positive feedback effect. Taking Chengdu and Mianyang as examples, the agglomeration of high-tech industries has driven population concentration and mobility (60), while simultaneously triggering land use pattern restructuring. However, excessive intensive development has led to a decline in per capita public service resources (34). This "high-density, high pressure" coupling model resulted in infection risks in core urban areas far exceeding surrounding regions during the pandemic, confirming the risk accumulation effects brought about by economically driven spatial restructuring.

Second, the economic-social coupling in northeastern Sichuan manifests as a bidirectional inhibitory effect. A representative case



was the “May 09” outbreak in Guang’an, where monthly infections surged to 1,299 cases. This episode revealed that the region’s per capita medical expenditure lagged behind the provincial average, with medical facility shortages directly accelerating epidemic spread. The event not only demonstrated how infrastructure vulnerability amplifies risk transmission, but more importantly exposed the underlying mechanism: sluggish economic development severely constrains public service investment (67), while inadequate social protection simultaneously restricts human capital development and suppresses economic growth by weakening consumption capacity.

Third, the economic-environmental coupling demonstrates distinct stress effects in industrial cities, particularly evident in Nanchong, Yibin, and Mianhu. The expansion of traditional industries (e.g., liquor manufacturing in Yibin, textile and chemical production in Nanchong) has driven increased PM2.5 concentrations and water quality deterioration. Insufficient environmental protection investment further exacerbates health risks, empirically validating how the tension between development intensity and ecological carrying capacity translates into public health threats.

Fourth, the coupling coordination between spatial and economic systems is particularly prominent in Panzhihua. Through measures including intensive mining area redevelopment, functional diversification in central urban zones, and strict ecological conservation management, the city has achieved optimal alignment between spatial resource allocation and economic development needs. This spatial optimization strategy has established Panzhihua as a zone city in China’s national comprehensive resource utilization pilot zones. Such a coordinated development pathway provides replicable practical solutions for peer cities to construct resilient industry-spatial-ecological systems.

Fifth, the synergistic effects of space-society-environment systems are prominently demonstrated in Guangyuan City. As Sichuan Province’s highest CCD-scoring city (CCD = 0.855), Guangyuan has achieved virtuous interaction between social systems and environmental governance through its “low-density, high-investment” development model. Leveraging its mountainous topography to create a polycentric spatial configuration, the city maintains relatively low population density while compensating for economic development limitations through extraordinary healthcare resource allocation and robust social security systems. This governance approach—integrating decentralized spatial structures, premium ecological endowments, and targeted social investments—has not only significantly reduced epidemic transmission risks but also established a distinctive resilient development paradigm for mountainous cities. It provides valuable inference for coordinating socioeconomic development with ecological conservation in underdeveloped western regions.

These coupling mechanisms not only deconstruct the generative logic of risk heterogeneity, but also empirically validate through typical cases a transmission chain of industrial agglomeration (economic) → land-use compactness (spatial) → service coverage (social) → ecological sensitivity (environmental). This provides a differentiated theoretical framework for regional resilience planning.

4 Discussion and research contributions

4.1 Discussion

The coordinated development between infectious disease hazards and urban vulnerability constitutes a critical component

of urban public health risk governance [68]. These two systems interact through factor flows and feedback mechanisms, collectively determining regional comprehensive risk levels. This study has measured infectious disease hazards, urban vulnerability, comprehensive risks, and coupling coordination, with regional distribution patterns visualized through spatial mapping techniques.

4.1.1 Validation of the CCD model

This study validated the coupling coordination degree (CCD) assessment results using cumulative infection case data from prefecture-level cities in Sichuan Province between January 1, 2020 and December 31, 2021. The case-growth increment ($\Delta C = C_{2021} - C_{2020}$) was employed for verification, generating ΔC and CCDI total statistics maps for each city (Figure 11—the Y-axis values of CCD were magnified for detail display, while case increment data were compressed to a 3,000-range display, though Chengdu's values remained the provincial maximum).

The results show that Chengdu exhibited the highest case growth increment (18,341 cases) in the province, far exceeding other cities, which corresponds with its lowest CCDI (0.024) in Sichuan. In striking contrast, Panzhihua recorded the lowest case growth increment (71 cases), demonstrating an inverse relationship with its high CCD index (0.619).

The research findings demonstrate a significant negative correlation between epidemic development and coupling coordination degree (CCD) across Sichuan Province's cities during the Omicron variant outbreak. Cities with higher CCD values (e.g., Panzhihua) exhibited stronger epidemic resistance capabilities, maintaining relatively low case growth increments. Conversely, cities with lower CCD values (e.g., Chengdu) faced substantially greater epidemic prevention and control pressures. These results indicate that the CCD model can effectively predict case number trends across cities, validating the model's accuracy and applicability in assessing regional epidemic prevention efficacy [69]. The findings provide scientific evidence for formulating differentiated prevention and control strategies.

4.1.2 Comparative analysis with conventional risk models

The comparative analysis between the CCD model and traditional risk assessment models (Table 1) demonstrates that the CCD framework transcends the linear paradigms of conventional approaches (e.g., weighted summation or multiplicative models). Its fundamental innovation lies in capturing dynamic feedback mechanisms while quantitatively characterizing the synergistic interactions between hazards and vulnerability through coupling degree (C) and coordination degree (T), enabling the identification of vicious cycles such as accelerated disease transmission resulting from medical resource depletion [70]. By leveraging the spatial heterogeneity characteristics of coupling coordination degree (T), the model overcomes the coarse-scale limitations inherent in regional averaging methods, thereby facilitating differentiated interventions across cities [71]. Moreover, the analysis of coordination lag types (hazard-dominant versus vulnerability-dominant) facilitates the mapping of priority measures, effectively circumventing the resource misallocation associated with traditional homogeneous high-alert interventions [72]. Consequently, the coupling coordination degree model has emerged as a robust analytical tool for evaluating balanced regional development.

4.2 The main contributions of this study

This study developed a "hazard-vulnerability" risk coupling model based on the entropy method and Coupling Coordination Degree (CCD) model, systematically analyzing coupling coordination mechanisms and key influencing factors. The results reveal that the regional risk coupling system exhibits a distinct "high in central areas, low in peripheral regions" spatial differentiation pattern, where economic vulnerability, spatial vulnerability, and social vulnerability demonstrate complex nonlinear interactions.

To verify the reliability of research conclusions, this study conducted systematic validation through a triple-verification approach: First, correlation analysis between cumulative confirmed

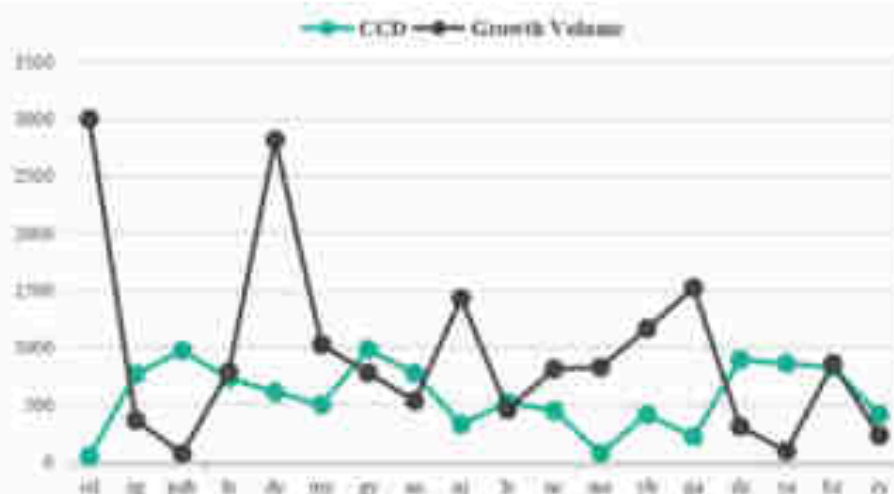


Figure 11
Comparative display of coupling coordination degree and case growth volume.

TABLE 7 Comparative analysis of CCD model vs. traditional models.

Dimension	Traditional models (INFORM, PVU)	CCD model	Comparative framework
Risk composition	Linear additivity $R_k = \sum_{i=1}^n W_i \times X_i$	Nonlinear coupling $C = 2 \times \frac{\sqrt{H \times V}}{\sqrt{(H+V)^2}}$ $T = \omega \frac{H}{V} + \beta \frac{V}{H}$ $D = \sqrt{C \times T}$	Captures synergistic interactions between hazard and vulnerability (Synergistic Interactions)
	$R_k = H_k \times V_k$	$C = \frac{(H(x)^2 + V(x)^2)}{(H'(x) + V'(x))^2}$ $T = \sqrt{H'(x) \times V'(x)}$ $D = \sqrt{C \times T}$	
Mechanism	Differential Causality (e.g., Vulnerability → Risk)	Bi-directional Feedback Loops (e.g., Medical surge → Transmission acceleration → Vulnerability)	Describes dynamic systemic risk events (Dynamic feedback mechanisms)
Output	Static risk scores	Coordination type (e.g., Low coordination) + Lag direction (e.g., Hazard-lagged/Vulnerability-lagged)	Identifies priority domains for risk governance (Spatial heterogeneity)
Policy recommendations	Heterogeneous interventions via static zoning Administrative unit allocation → Standardized policy deployment	Heterogeneous leverage regulation via Dynamic Feedback: feedback diagram → Targeted governance	Transforms passive response to proactive risk diaging, enabling context-sensitive strategies (Customized Interventions)

cases and the comprehensive risk assessment system across prefecture-level cities in Sichuan Province confirmed the predictive validity of the evaluation framework. Second, cross-validation between the risk model and coupling model revealed a significant negative correlation, demonstrating that improved coupling coordination degree effectively reduces systemic risks. Finally, verification analysis between regional case growth increments and coupling coordination degree further ensured the robustness of research findings. These validation results provide a solid empirical foundation for subsequent policy recommendations.

Building upon these research findings, this study proposes differentiated governance strategies:

1) Optimization strategies for the Chengdu Plain region

Given Chengdu's distinctive "low vulnerability-high risk" profile, systemic optimization strategies should be implemented. First, within the Chengdu-Chongqing Economic Circle framework, priority should be given to developing regional growth poles such as Maoyang Science City and the Yibin-Luzhou industrial corridor. This can be achieved through industrial policy guidance and infrastructure interconnectivity to promote polycentric network development, thereby effectively alleviating single-core agglomeration pressures.

Second, urban spatial expansion should incorporate enhanced ecological resilience planning. This includes reserving ecological buffer zones along the outer ring expressway and connecting them through greenway systems to form emergency evacuation networks. Simultaneously, new urban developments should mandatorily reserve convertible emergency land parcels with pre-installed medical equipment interfaces.

Furthermore, structural adjustments to medical resources should be implemented via a "branch hospital system + tiered diagnosis and treatment" model.

These measures will ultimately establish a multidimensional prevention system encompassing "spatial decentralization—ecological buffering—emergency preparedness—medical resource balancing," systematically mitigating public health risks in high-density urban areas.

2) Balanced development pathway for northeastern Sichuan region

To address the concentration of impoverished populations and inadequate infrastructure in northeastern Sichuan, a systematic development strategy should be designed.

First, priority should be given to cultivating competitive local industries such as specialty agriculture and green processing manufacturing, which can be achieved by establishing return-to-hometown entrepreneurship subsidies and industrial development funds to reverse emigration trends and boost local employment.

Second, the returning population should be leveraged to drive local fiscal revenue growth, with newly increased public finances being preferentially allocated to upgrading medical facilities and improving transportation infrastructure to enhance public service delivery.

Ultimately, this integrated approach will establish a virtuous development cycle of "industrial revitalization → population agglomeration → fiscal expansion → service improvement," fundamentally strengthening regional resilience. This cyclical model not only addresses critical infrastructure deficiencies but also achieves sustainable development through endogenous growth drivers.

3) Transformation strategies for environmentally stressed cities

For environmentally stressed cities like Yibin and Nanchong, a development path coordinating industrial transformation with environmental governance should be adopted.

First, ecological transformation of key industries should be implemented to reduce pollution intensity through industrial structure optimization.

Second, environmental protection investments should be significantly increased through creating ecological compensation mechanisms, designating health protection buffer zones around major industrial parks, and building a tiered environmental risk prevention system.

Additionally, supporting environmental health monitoring networks should be constructed to enable real-time warnings of pollution sources and health risks.

Through this triple-intervention approach of "industrial upgrading → environmental governance → health protection," environmentally high-risk cities can transition toward green development models.

4. Optimization and upgrading directions for Panzhihua

As a successfully transitioned resource-based city, Panzhihua has demonstrated outstanding performance in industrial-spatial-ecological coordination, yet requires targeted enhancements in healthcare and social security systems.

First, healthcare system improvements should be prioritized by increasing medical expenditure ratios and optimizing resource allocation.

Second, the current emergency supplies reserves are insufficient, necessitating the establishment of a three-tier allocation system encompassing municipal, county, and mining district levels.

Third, social insurance coverage expansion should be accelerated, particularly for vulnerable groups like miners, through customized insurance schemes and awareness campaigns.

Through this integrated approach of "medical investment → emergency preparedness → insurance coverage," the city will systematically address existing gaps while reinforcing its sustainable development advantages.

5. Sustainable development pathway for Guangyuan City

As an exemplary model of resilient mountain city development, Guangyuan has achieved remarkable success in spatial-social-environmental coordination, yet requires focused improvements in economic development levels.

First, economic scale expansion should be prioritized by addressing the below-average per capita GDP through targeted growth initiatives.

Second, industrial support strengthening should be implemented by cultivating regionally influential leading industries to address the current lack of driving industries.

Third, fiscal capacity building should be enhanced by improving financial self-sufficiency rates and accelerating infrastructure development to overcome current limitations.

Through this integrated approach of "specialty industry cultivation → fiscal mechanism innovation → infrastructure improvement," the city will effectively enhance endogenous growth drivers and sustainable development capacity.

5 Conclusion

This study innovatively constructs a "hazard-vulnerability" risk coupling model, introducing spatial coupling theory into the field of

public health risk management. By employing the entropy method and coupling coordination degree model, it reveals significant spatial heterogeneity characteristics and dynamic interaction mechanisms between infectious disease transmission risks and urban systems, overcoming the limitations of traditional linear risk assessment approaches. Furthermore, the study identifies key factors across different coupling coordination types, providing scientific evidence for formulating differentiated risk prevention strategies and urban resilience solutions.

The results indicate that the coupling coordination degree (CCD) between infectious disease hazards and urban vulnerability in Sichuan Province remains at a relatively low level overall (mean = 0.584). Panzhihua and Guangyuan demonstrate optimal coordination states (with CCD values of 0.649 and 0.655 respectively), while Chengdu exhibits a characteristic "low vulnerability-high hazard" pattern (CCD = 0.031). The region displays a distinct core-periphery spatial differentiation pattern, where cities with imbalanced development are predominantly concentrated in the Chengdu Plain and southern Sichuan regions—a distribution showing significant correlation with the socioeconomic gradients of Sichuan's four major economic zones. Notably, further typological analysis reveals a prevalent "hazard-dominant lagging" coupling coordination characteristic across the province, which has been corroborated by vulnerability assessments of urban public health systems in relevant planning documents.

Further analysis reveals dual characteristics in the mechanisms influencing urban coupling coordination degree (CCD): on one hand, there exist significant interactions among economic-spatial-social-environmental factors; on the other, these coupling relationships demonstrate pronounced spatial heterogeneity. The study demonstrates that regional coordinated development requires differentiated governance strategies: the Chengdu Plain region should focus on constructing a multidimensional prevention system encompassing "spatial decentralization-ecological buffering-emergency preparedness-medical resource balancing"; northeastern Sichuan needs to establish a virtuous cycle of "industrial revitalization-population agglomeration-fiscal expansion-service improvement"; environmentally stressed cities should prioritize coordinated transformation through "industrial upgrading-environmental governance-health protection"; transition cities like Panzhihua must perfect their social security networks via "medical investment-emergency preparedness-insurance coverage"; while resilient mountainous cities such as Guangyuan should strengthen their development pathway through "specialty industry cultivation-fiscal mechanism innovation-infrastructure improvement."

This study establishes an analytical framework that provides crucial decision-making support for regional development planning and public health emergency system construction in Sichuan Province. Specifically, the differentiated intervention strategies proposed for regions with distinct characteristics can guide the optimization of public health resource allocation and the implementation of urban resilience-building projects. The research outcomes not only offer valuable references for infectious disease prevention and control in rapidly urbanizing areas, but also provide theoretical foundations for achieving healthy city initiatives and sustainable development goals.

It should be noted that this study still has several aspects requiring further development. First, the factor analysis on urban vulnerability assessment needs strengthening, and future research could introduce more comprehensive spatial variables and governance effect variables

to improve the evaluation system. Second, while the entropy method can objectively reflect data characteristics, its results may be influenced by data distribution—subsequent studies could incorporate other weighting determination methods like the Analytic Hierarchy Process for verification. Finally, the applicability of research conclusions drawn from western provinces to eastern developed regions requires validation. Future studies should expand the research scope and conduct comparative analyses of regional characteristics at different development stages to enhance the generalizability of findings.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy. Requests to access these datasets should be directed to the corresponding author at qianqian@scnu.edu.cn.

Ethics statement

Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article because the data used in this study were obtained from publicly available epidemic records (2022) released by the Sichuan Provincial Health Commission and urban statistical yearbooks, with all personally identifiable information having undergone anonymization processing.

Author contributions

LL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. JQ: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. MY: Validation, Writing – review & editing. SM: Conceptualization, Resources,

Writing – review & editing. XC: Validation, Writing – review & editing. MC: Visualization, Writing – review & editing. WL: Software, Writing – review & editing.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Gershgoren SD, Linder J, Lerner E, Pyles OG, Ibrahim A, Holmes RC, et al. Tracking virus outbreaks in the 21st-century first century. *Nat Microbiol*. (2019) 4:13–4. doi: 10.1038/s41564-018-0296-2
2. Fan LL, Zhang S. From fighting COVID-19 pandemic to building sustainable development goals: An opportunity for sustainable information systems research. *Inf J Inf Manag*. (2020) 22:101196. doi: 10.1016/j.infsmg.2019.101196
3. Chendrasekhar A, Jey LK, Z Dawood A. General commentary: whether infection has interrupted the spread of infectious disease—revised question by the COVID-19 pandemic. *Front Public Health*. (2022) 10:877330. doi: 10.3389/fpubh.2022.877330
4. Aguilera J, Rosales A, Gonzalez C, Gonzalez E, Roldan A, Marachi M, et al. Impact of urban structure on infectious disease spreading. *Soc Rep*. (2022) 12:3416. doi: 10.3389/fpsyg.2022.847204
5. Dai S, Zhang J, Wang H. Identification of overcrowding in a single-sided building with natural ventilation: case of transient pollution dispersion. *J Build Eng*. (2023) 68:100449. doi: 10.1016/j.jobe.2023.100449
6. Kato-Horino A, Lurie P. The risk of nosocomial pneumonia in patients with complex networks. *Int J Infect Dis*. (2021) 105:16. doi: 10.1016/j.ijid.2021.06.029
7. Vintar J, Brink D. The influence of urban, socio-economic, and geo-environmental aspects on COVID-19 cases, deaths and mortality: a multi-city case in the Atlantic Forest, Brazil. *Environ Cities*. (2021) 13:102894. doi: 10.1016/j.encl.2021.102894
8. Jin QH, Jing L, Jiding MAO, Yi Li. Research framework of city vulnerability and planning responses in the post-pandemic of major systems. *City Plan*. (2020) 44:11–21.
9. Rahayu E, Rini EE, Andani S, Putri RA. Development and urbanization during the COVID-19 pandemic: regional vulnerability in Java, Indonesia. *Trans Plan Rev*. (2023) 68:411–45. doi: 10.1016/j.tranpol.2022.12
10. Yu H, Li X, Yi J, Mo B, Liu P, Tian P. Whether urbanization has interrupted the spread of infectious diseases—revised question by the COVID-19 pandemic. *Front Public Health*. (2023) 11:1080716. doi: 10.3389/fpubh.2023.1080716
11. Li M, Wu YD. COVID-19 cases and mortality. *Appl Geogr*. (2023) 140:104918. doi: 10.1016/j.apgeog.2023.104918
12. Viscusi F, Lippi P, Alderman H, Giannini D, Williams AM, Bapat S, et al. Drawing a pandemic vulnerability map: the 105th global vulnerability assessment digital and report. *Front Econ*. (2023) 4:127647. doi: 10.3389/fec.2023.127647
13. Liu W, Zhou Z, Li H, Zheng H, Liu Y. Urban resilience assessment and its spatial correlation from the multi-dimensional perspective: a case study of four provinces in north-north China. *Urban Clim*. (2024) 101:103510. doi: 10.1016/j.uclm.2023.103510
14. Gandy M. THE 2008/2009 CITY urban political ecology and the pandemic imaginary. *Int J Urban Regional Res*. (2023) 46:242–15. doi: 10.1111/ijur.1466

15. Yang W, Wang K, Zhang L, Xu X. COVID-19, urbanization pattern and economic recovery: An analysis of Hubei, China. *Urban Geogr* (2020) 17:1077–108. doi: 10.1080/01448758.2020.1770777
16. Pacheco M, Malachuk H, Mervin A. Estimating post-pandemic urban transformations: a literature review on COVID-19's influence on urban design. *Sustainability* (2020) 12:10303. doi: 10.3390/s121030303
17. Connolly C, Ball K, Mills R. Urbanization and the spread of infectious disease: demographic change, infrastructure and governance. *Urban Stud* (2021) 58:245–67. doi: 10.1177/0042098520931803
18. Gao X, Li G, Wang J, Su T. Spatiotemporal evolution, pattern of diffusion, and influencing factors of the COVID-19 epidemic in Hubei Province, China. *Chin Med Virol* (2021) 94:1181–93. doi: 10.1186/s13041-021-02702
19. Costa GB, Casarin FEA, Keller R. Applicability of geographical information systems (GIS) in tracking COVID-19: a systematic review. *J Geogr Spat Anal* (2020) 2:29. doi: 10.1007/s43111-020-00191-2
20. Ayari T, Bouder F. The COVID-19 pandemic: how can risk science help? *J Risk Res* (2020) 23:449–54. doi: 10.1080/13698575.2020.1756260
21. Ayari T. Risk assessment and risk management: review of recent advances on flood evaluation. *Eur J Oper Res* (2016) 254:1–11. doi: 10.1016/j.ejor.2015.10.029
22. Ma S, Li S, Zhang J. Diverse and nonlinear influences of built environment factors on COVID-19 spread across homophily in China at its initial stage. *Sci Rep* (2021) 11:1–15. doi: 10.1038/s41598-021-01880-4
23. Baika R, Dohi M, Parnis J, Popela J, Pita E, Roberts E. Review of current approaches to spatially explicit urban vulnerability assessments: hazard complexity, data sources, and cartographic representations. *Environ* (2016) 14:42–61. doi: 10.1038/nature.2016.20160
24. Parnis A, Huthwaite C, Kruse J. Benefits and challenges of resilience and vulnerability for disaster risk management. *Int J Disaster Risk Red* (2014) 3:2–20. doi: 10.1016/j.ijdrr.2014.04.004
25. Metz S, Nussler M, Göl M, Griesler E. An integrated hybrid SCDM approach to evaluate countries' COVID-19 risks. *Asian Econ Plan Sci* (2021) 10:101744. doi: 10.1039/c9cp00000a
26. Pang S, Shi X, Wen Z. Environmental risk assessment and comprehensive index model of disaster loss for COVID-19 transmission. *Environ Technol Innov* (2021) 12:101587. doi: 10.1016/j.eti.2021.101587
27. Pichay A, Bando AK, Giordano B, Dufresne G, Latour N, Le Moëlle K, et al. A novel methodology for qualitative risk assessment of COVID-19 outbreak. *Int Rev* (2021) 11:1–20. doi: 10.1039/c1cp00000a
28. Kango S, Ming C, Sridharan, Farooq M, Northcott MA, Singh SK. Analyzing the risk to COVID-19 infection using online seating and GIS. *Risk Anal* (2021) 41:401. doi: 10.1111/risa.13734
29. Schwab J. COVID-19: a risk assessment perspective. *ACS Chem Health Saf* (2020) 17:566–8. doi: 10.1021/acschemhealth.0c00005
30. Bai Q, Wu Y, Shi S, Ye C, Zou Z, Zhang Z, et al. Epidemiology and transmission of COVID-19 in 351 cases and 1286 of their close contacts in Shenzhen, China: a retrospective cohort study. *Lancet Infect Dis* (2020) 20:911–9. doi: 10.1016/S1473-3099(20)30261-5
31. Wang CL, Pruthi RA, Srinivas L, Srinivas B, Lakshana S, Tubbis Z, et al. Airborne transmission of respiratory viruses. *Nature* (2021) 592:461–148. doi: 10.1038/s41586-021-03910-0
32. Siddiqui R, Cavazzini G, Maltin A, Gaudin P. Fast prototype of the infectious disease system (IDS) software for prompt identification of infectious disease. *BMJ* (2020) 369:57. doi: 10.1136/bmj.n200714001
33. Anshu Yous C, Ullman Fawcett PC, Abu Anyeha D. Risk analysis and hot spot detection of SARS-CoV-2 in Nigeria using demographic and environmental variables: An early assessment of transmission dynamics. *Int J Environ Health Res* (2021) 52:111–22. doi: 10.1080/09637259.2021.1934886
34. Ibrahim K, Salama M, Bari M, Hagar I, Patel PE, Pirmasri M. A district level mapping and vulnerability assessment of the COVID-19 pandemic's impact in India. *Spat Spatio Temp Epidemiol* (2021) 34:100380. doi: 10.1016/j.sste.2020.100380
35. Su B, Lu X, Tian Y, Xu G, Ju Z, Chinakha N. Population flow drives spatiotemporal distribution of COVID-19 in China. *Nature* (2020) 582:65–68. doi: 10.1038/s41586-020-2284-7
36. Tatem KJ, Lamoreaux J, Malachuk HA, Lewis H, Gossard NG, Tallis G. An assessment of the geographical risk of wild and zoonotic zoonotic outbreaks in Africa and Asia. *PLoS Infect Dis* (2017) 13:1–14. doi: 10.1371/journal.ppat.1005404
37. Sheth N, Kapadia M, Mousavi M, Puri R, Harris de León RM, Berman Appleby ME, et al. Assessing urban centers' preparedness to global risks in analysis of the global south from COVID-19 perspective. *Habitat Int* (2021) 110:102517. doi: 10.1016/j.habitat.2021.102517
38. Murtaza B, Murtaza U, Ograslan U, Durrani M, Patel A, Durrani N, et al. Population vulnerability to the SARS-CoV-2 virus infection: A county level geographical methodological approach in Romania. *Geoforb* (2021) 52:102700. doi: 10.1016/j.geoforb.2021.102700
39. Khan MA, Rabi KH, Hossain R, Sultana R, Hossain E, Hossain SA, et al. Household socioeconomic vulnerability assessment due to COVID-19 outbreaks: a web-based survey in Bangladesh. *Electron J Inform Med* (2021) 19:100180. doi: 10.2997/ejimm.1707
40. Pardo L, Malague R, Gomez J, Lado E. Urban vulnerability assessment for pandemic surveillance—the COVID-19 case in Bogotá, Colombia. *Sustainability* (2021) 13:4012. doi: 10.3390/s13064012
41. Caselli R, Haines CR. Community vulnerability and resiliency: what matters most in space-temporal modeling of the COVID-19 pandemic? *Int J J Geogr* (2021) 20:114105. doi: 10.1186/s13041-021-11479-1
42. Fall S, Malafa E, Quanzah I, Frankha MJ, Whaley-Grimes T. County-level assessment of vulnerability to COVID-19 in Alabama. *Geogr Int J Geogr* (2021) 11:320. doi: 10.1186/s13041-021-11507-8
43. Tiller J. Urban density and Covid-19: towards an adaptive approach. *World Cities* (2021) 2:139–45. doi: 10.1177/26390
44. Wang X, Viera Caroline R, Pagan C. Urban pandemic vulnerability and COVID-19: a new framework to assess the impacts of global pandemics in the metropolitan region of Amsterdam. *Sustainability* (2021) 13:4284. doi: 10.3390/s13074284
45. Xia H, Lu X, Zhao W, Zhao W, Lu X, Wu X, et al. Spatio-temporal changes of ecological vulnerability across the Qinghai-Tibetan plateau. *Ecol Ind* (2021) 123:107374. doi: 10.1016/j.ecolind.2020.107374
46. Xu Y, Xu X, Gu K, Zhu K, Hu L, Ding J. An assessment of renewable energy development in hot and cold temperate countries: an entropy and TOPSIS approach. *Energy Rep* (2020) 10:2543–50. doi: 10.1016/j.energy.2021.105486
47. Li X, Wang X, Li X, Zhou J, Fan C, Guo N. Zoning technology for the management of ecological and environmental vulnerability risk zones: clustering and entropy-weighted TOPSIS: a case study in Beijing. *J Clean Prod* (2021) 307:127440. doi: 10.1016/j.jclepro.2021.127440
48. Rizzo-Lemus J, Anand A, Chandra R, Kumar AA, Gupta D. Evaluating urban flood risk using hybrid method of TOPSIS and machine learning. *Int J Disaster Risk Red* (2021) 60:102614. doi: 10.1016/j.ijdrr.2021.102614
49. Zhang X, Hailu M, Fan CT, Chakraborty A, Nishikawa M, Gu L. An integrated flood risk assessment approach based on coupled hydrological hydraulic modeling and bottom-up based vulnerability analysis. *Environ Model Softw* (2021) 134:105129. doi: 10.1016/j.envsoft.2021.105129
50. Han J, Wang B, An Y, Rahman H, Chai B. The coupling and coordination degree of urban resilience system: a case study of the Changsha–Changsha urban agglomeration. *Environ Impact Assess Rev* (2020) 101:101740. doi: 10.1016/j.envimp.2021.101740
51. Gong L, Longwen L, Zhenbo W, Longwen C, Faming Z. Expression of coupling effect in the economy–society–environment system in urban area: case study of the Yangtze River Delta urban agglomeration. *Ecol Ind* (2015) 66:10788. doi: 10.1016/j.ecolind.2015.10788
52. Li J, Shi W, Li M, Wang L. Coupling coordination degree of production, living and ecological status and its influencing factors in the Yellow River Basin. *J Clean Prod* (2021) 298:126801. doi: 10.1016/j.jclepro.2021.126801
53. Yang Y, Wei W, Li Y. Coupling coordination analysis of rural production–living–ecological space in the Beijing-Tianjin-Hebei region. *Ecol Ind* (2020) 117:106111. doi: 10.1016/j.ecolind.2020.106111
54. Yang Z. An integrated approach to evaluating the coupling coordination between tourism and the environment. *Tourism Manag* (2019) 70:71–9. doi: 10.1016/j.tourman.2019.06.001
55. UWW, YL, PT, Zhang DK, Li W, W, P, Zhang D, et al. Assessment of coordinated development between social economy and ecological environment: case study of inland flood cities in northwestern China. *Environ Geosci* (2019) 19:102208. doi: 10.1038/s41566-020-02228-7
56. Chang Q, Shi Y, Chen Y. The coupling coordination and influencing factors of urbanization and ecological resilience in the Yangtze River Delta urban agglomeration. *China Land* (2024) 11:111. doi: 10.3390/land11010111
57. Yang M, Wu C, Song L, Sun G. Coupling coordination relationship between cultural heritage conservation and socio-economic system in ethnic villages of Southeast Guizhou. *Land* (2024) 13:123. doi: 10.3390/land1308123
58. Xiang M, Yang J, Han S, Liu Y, Wang C, Wei F. Spatial coupling relationship between multidimensional poverty and the risk of geological disaster. *Land Environ* (2021) 28:652–66. doi: 10.1080/14488044.2021.2087077
59. Jiang Z, Qi Q, Cui Y. Discussion on the coupling relationship between flood risk and population vulnerability from climate justice. *J Water Resour Chang* (2021) 15:1076–89. doi: 10.1007/s12665-021-10072-2
60. Liu L, Su K, Fan H, Zhang Y, Shi B. Urban flood risk assessment (revisiting the relationship among hazard, exposure, and vulnerability). *Environ Sci Technol* (2021) 55:4645–57. doi: 10.1021/acs.est.1c03747
61. Wu B, Huang Q, Zhou L, Wu Q, Deyuan M. Spatial-temporal evaluation of urban resilience in the Yangtze River Delta from the perspective of the coupling coordination degree. *Environ Sci Technol* (2020) 27:400–11. doi: 10.1007/s10668-021-01687-2
62. Su K, Gao H, Xu J, Li G, Han L, Fu Y, et al. Spatial coupling relationship between ecological fragility and economic poverty in Hengshui County of Ningxia. *Chin Geogr Res* (2021) 28:227–39.
63. Zhu Z, Zhang T. Flood disaster risk assessment based on fuzzy logic algorithm. *Natural Comput Appl* (2021) 34:5445–51. doi: 10.1007/s00321-021-01707-8

84. Xiao T, Zhai Y, Wu Q, Tang Y, Jiang H, Ning L, et al. Proposed WPIQR method for groundwater vulnerability assessment in karst phreatic aquifer, Shandong Province, China: a case study. *Environ Earth Sci*. (2019) 73:133–46. doi: 10.1007/s12663-019-4903-8
85. Zaman T, Jager M, Jahan M. A new empirical estimator for analysis of COVID-19 risk. *Geospat Comput Environ Exper*. (2021) 34:6886. doi: 10.1080/15487717.2021.1919811
86. Guo X, Qin Z. Research on the level of high-quality urban development based on big data evaluation system: a study of 10 prefecture-level cities in China. *Sustainability*. (2020) 12:478. doi: 10.3390/su12030478
87. Chang M, Huang L, Zhao T, Zhu J, Mo Y, Li L, et al. A challenge of sustainable urbanization: mapping the equity of urban public facilities in multiple dimensions in Zhongshan, China. *Land*. (2013) 2:1143. doi: 10.3390/land20912891346
88. Kishor N, Chongong Y, Omer A, Xing J. Health security capacities in the context of COVID-19 outbreak: An analysis of international health regulations around report data from 182 countries. *Emerg*. (2020) 39:1047–53. doi: 10.1016/j.emerg.2020.02.003
89. Cao T, Liu W, Zhang J, Liu Y, Zhang H, Zhao Z, et al. Nighttime light perspective in urban indicator assessment and spatiotemporal impact of COVID-19 from January to June 2022 in mainland China. *ISPRS Int J Geo-Inf*. (2023) 12:1009. doi: 10.3390/ijgi12071009
90. Li W, Wang Y, Xie S, Cheng X. Coupling coordination analysis and spatiotemporal heterogeneity between urbanization and ecosystem health in Chongqing municipality, China. *Sci Total Environ*. (2021) 790:148311. doi: 10.1016/j.scitotenv.2021.148311
91. Dong J, Jiang Q, Liu H, Jiang Z, Gu C, Li D. The coupling coordination between health service supply and regional economy in China: spatial-temporal evolution and convergence. *Front Public Health*. (2020) 8:352344. doi: 10.3389/fpubh.2020.232344
92. Bi Y, Zhang L, Wang Q, Li J, Yang H, Zhang R. Coupling relationship between urbanization and water-related ecosystem services in China's Yangtze River Economic Belt and its socio-ecological driving forces: a county-level perspective. *Ecol Econ*. (2023) 196:109971. doi: 10.1016/j.ecolecon.2023.109971

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How does urban amenity affect the willingness of college youth to stay in the city?—empirical evidence from Chinese first-tier cities

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Introduction: For countries in the process of transition from a traditional economy to a knowledge-based and innovative economy, talent is the key to ensure the success of the transition. As the main source of talents, youth in colleges are the foundation and important driving force of social and economic development, and their willingness to stay in the city is of great significance to the development of the city. Previous studies have shown that urban amenity is the attraction of the city to talents, and this study aims at exploring the impact of urban amenity on the willingness of youth in colleges to stay in the city.

Methods: First, based on the scientific scale development process, we developed the urban amenity scale based on the subjective evaluation of urban residents. Second, through questionnaire survey, the developed scale was used to verify the positive impact of urban amenity on the willingness of youth in colleges to stay in the city. And the binary logit model was employed in this study.

Results: This study finds that urban amenity positively affects the willingness of colleges youth in first-tier cities to stay in the city. The three dimensions of urban amenity—urban work amenity, urban life amenity, urban cultural amusement and study amenity—all positively affect the willingness of college youth to stay in the city. Moreover, by comparing the Odds Ratio of college youth's willingness to stay in the city in first-tier cities, it is found that urban cultural amusement and study amenity has the greatest impact on the willingness of college youth to stay in the city, second is urban life amenity, and the last is urban work amenity.

Discussion: The findings of this study add nuance to the global literature by demonstrating that for Chinese college youth, urban amenities are not a replacement for economic concerns but a complement. The significance of all three dimensions of amenity shows that Chinese talents seek a "complete package". It means a city that should offer strong career prospects (work amenity), a convenient and stable daily life (life amenity), and opportunities for personal enrichment and social belonging (cultural and study amenity). Western studies often highlight a tension between economic and cultural drivers, our results from China suggest a more integrative model.

KEYWORDS

urban amenity, youth in colleges, talents, willingness to stay in the city, scale of urban amenity

1 Introduction

At present, China is undergoing a transformation from a traditional economy to a knowledge-based and innovative economy. Talent is the key to the success of the transformation. In the era of a knowledge-based economy, human resources are gradually replacing capital, land, and other production factors, which becomes the core force for promoting economic growth and enhancing urban competitiveness (1). To attract and gather high-quality talent resources, large or medium-sized cities in China have formulated and introduced a series of talent policies, including granting housing subsidies and giving municipal citizenship (2). However, these talent policies can only attract talent in the short term and have little impact on their long-term residence. Whether talents stay in the city or not is a comprehensive evaluation of the city based on their own needs, which is a complex decision-making process and is not solely influenced by talent policies. College youth are an important talent resource, and the factors influencing their willingness to stay in the city are worth exploring.

Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-range Goals to 2035 (an important document issued by the Chinese government to plan economic and social development) clearly puts forward concepts and goals such as "enhancing convenience and improving service experience," "comprehensively improving urban quality," and "improving social civilization." These reflect that the factors of living quality, such as urban public services and social environment, have become increasingly important. At the same time, China is in a new stage of development, with per capita income and education levels generally rising (3). Therefore, youth have increasingly higher requirements for a qualitative urban living experience. It is not difficult to find that the more convenient and better the living experience of Chinese cities is in reality, the stronger the willingness of young talent to stay. By reviewing the relevant literature, we can see that the urban amenity that focuses on talent attraction could explain this phenomenon well. The theory of urban amenity is condensed in the discussion of the driving forces that promote urban development. According to this theory, the ability of attracting talents has replaced material and geographical advantages, which becomes the main driving force in promoting urban development, and urban amenity is the attraction of a city to talents (4–6).

In the era of a knowledge-based economy, urban amenities play an increasingly important role in attracting talent. Previous studies have verified the impact of urban amenity on the dwelling willingness of mobile talents (7), but it has not been extended to the field of youth talents in college. Cities in China, such as Beijing, Shanghai, Guangzhou, and Shenzhen, are the first-tier cities with the highest level of economic development, the maximum number of colleges and universities, and a large number of foreign talents, which play an important supporting and leading role in Chinese economic and social development. Improving the dwelling willingness of youth in colleges of these four first-tier cities is an important starting point for high-quality urban development. Therefore, based on the urban amenity theory, this study explored the impact of urban amenity on the dwelling willingness of college youth talents to stay in cities.

2 Development of urban amenity scale

Ullman (8), who first proposed the concept of urban amenity, defined urban amenity as pleasant living conditions. Considering the obvious regional nature of urban amenity (9), believed that amenity is a local feature that cannot be marketed, and this feature can attract people to live or work here. From the perspective of industrial economics, Gottlieb (10) noted that amenity is a locally specific product or service that cannot be exported, and it can benefit employees as residents or commuters. In summarizing relevant studies (11), regarded urban amenity as a composite "product" in which cities use public infrastructure and public sector workers as capital and labor input. Although scholars have different emphases on the definition of urban amenity, they all believe that urban amenity is related to people's demand for pursuing a quality of life and has four main characteristics. First, urban amenity is regional and does not have a production function; second, urban amenity is not renewable, for example, once the wild environment is destroyed, it is irreversible; third, urban amenity is positively correlated with income, that is, it has higher income elasticity; fourth, urban amenity is generally irreplaceable (8).

Urban amenity is the core explanatory variable of this study. According to the previous literature, the measurement of urban amenity is mostly objective. Urban amenity measuring indicators are divided into four aspects: public consumer goods (such as the number of theaters per capita), aesthetic and physical environment (such as climate and beautiful buildings in the city), public service (such as schools, hospitals), and speed (such as travel traffic and distance from commercial service centers) (12). Chinese scholars divided the evaluation index of urban amenity into three categories: amenity of natural environment, amenity of service environment, and amenity of social culture (13). The amenity of the natural environment mainly refers to natural environmental conditions, including temperature, precipitation, light, atmospheric environment, water conditions, and green conditions. Amenity of service environment mainly refers to the life service environment, emphasizing artificially made, but different from nature (14), including the construction of infrastructure (such as transportation, electricity, and information technology), public services (such as schools, hospitals, and so on), and various entertainment facilities (for example, theaters, museums, cafes, and specialty restaurants). Social and cultural amenity mainly refers to the social environment and cultural landscape, including social inclusiveness, resident values, cultural atmosphere, and other related aspects. All these urban amenity evaluation indexes are objective, but lack a subjective evaluation of urban residents. Only when urban residents perceive urban amenities from daily life, work, study, and entertainment can they more truly reflect the city's amenities. Therefore, the development of an urban amenity scale based on urban residents' self-evaluation in accordance with rigorous and standardized procedures can not only enrich the existing urban amenity evaluation index system based on objective evaluation, but also provide a basis and reference for empirical research on urban amenity.

2.1 Generation of initial items

In view of the fact that the urban amenity scale should not only absorb existing studies, but also truly reflect the subjective perception of urban residents of urban amenity. This study mainly obtained the

initial items of the scale through the following steps. First, we sorted out the urban amenity evaluation indexes used in previous studies and summarized the common dimensions of all urban amenity evaluation indexes. Then, 30 residents from different cities were interviewed. The topic of the interview is "What kind of city do you think is an amenity? What are the most important aspects of amenity in your city? In terms of your daily life, study, entertainment, work, and so on, what makes this city an amenity for you?" Third, through the collation and analysis of literature and interview data, 30 initial items were formed,

2.2 Extraction of the items

The extraction process of the initial items is as follows. First, five college students majoring in urban management were invited to combine or delete 30 initial items in a lock-to-lock manner. Items that are agreed to have repetitive semantics, contain multiple semantics, and are unrelated to the topic have been deleted. After discussion, a consensus was reached on inconsistent or uncertain items, and 23 items were finally retained. Second, the 5-point Likert scoring method was used to compile the items, and after discussion and modification, the initial scale of urban amenity was formed.

2.3 Exploratory factor analysis

In this study, a questionnaire survey was conducted among residents of major cities in China, including Beijing, Shanghai, Guangzhou, Shenzhen, Wuhan, and Hangzhou. We distributed 400 questionnaires through the "questionnaire star" platform (it is a professional online platform for questionnaire surveys and voting). When collecting the questionnaires, we found 32 invalid ones (such as random answers, incorrect answers, incomplete answers, etc.). We deleted them and eventually collected 368 valid questionnaires, with a valid questionnaire recovery rate of 92%. In the valid samples, 31.64% were male and 48.36% were female. In terms of age, 29.22% were between 19 and 23 years old, 45.99% were between 23 and 26 years old, 17.63% were between 26 and 30 years old, and 7.56% were over 30 years old. In terms of education, 19.4% held a bachelor's degree or below, 59.7% held a master's degree, and 20.9% held a doctorate degree.

First, the reliability of each item is assessed by the corrected item-total correlation (CITC) coefficient; the items with a CITC coefficient less than 0.5 are eliminated. Accordingly, the item "The cost of living in this city is within your acceptable range" is excluded. The Cronbach's α value of the initial scale for the remaining 22 items is 0.953, indicating that the scale has good reliability. Second, Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests were performed on 22 items, and the results showed that the KMO value was 0.949, and the Bartlett's sphericity test reached a significance level of 0.001, indicating that the original data were suitable for factor analysis. Third, principal component analysis and the varimax rotation method are used for factor analysis. Factors are extracted according to the standard with an eigenvalue greater than 1, and items with a factor load value less than 0.5 are gradually removed from small to large, such as "The city's compulsory education resources are good, the school enrollment of (future) children is convenient. The city's climate, environment and other conditions are comfortable for you living here (less extreme weather, good air quality, and high urban

greening rate)," are deleted. There are 20 items remaining on the scale. Three common factors are extracted. Exploratory factor analysis was conducted again for the remaining items. The KMO value of the sample data was 0.947, and the Bartlett's sphericity test results were significant ($p < 0.001$). Three common factors were still extracted, the cumulative variance contribution rate reached 70.422%, and the factor load of each item was greater than 0.5. It can be seen from Table 1 that the Cronbach's α coefficient of the scale as a whole is 0.952, and the Cronbach's α coefficient of each factor is greater than 0.9, indicating that the scale has good reliability.

2.4 Confirmatory factor analysis

Validity testing is mainly concerned with detecting content validity and structural validity. First, the content validity of the original scale was tested by expert judgment. This scale was compiled based on a previous study on urban amenity, combined with objective indicators and the results of in-depth interviews with some urban residents, and entrusted teachers and students majoring in urban management to review and improve the items repeatedly. Therefore, the preparation of the scale is rigorous and standardized, and the content has certain reliability. Second, the measurement of structural validity includes both convergent validity and discriminant validity. The results show that the factor load of each item is greater than 0.5, the smallest average variance extracted (AVE) value among the three factors is close to 0.5, and the combined reliability (CR) value is greater than 0.8, indicating that the scale has good convergent validity. In addition, the arithmetic square root of the three factors' average variance extracted (AVE) value is greater than the correlation coefficient with the other factors (see Table 2), indicating that the scale has good discriminant validity.

With three common factors as latent variables, a confirmatory factor analysis test model was constructed. AMOS 26.0 structural equation software was used to analyze the structure of the three factors. Compared with the two-factor model and the single-factor model, the three-factor model had better goodness of fit (see Table 3). The absolute fitting index of the model showed $\chi^2/df = 1.924$ (less than 3), Root Mean Square Error of Approximation (RMSEA) = 0.07 (less than 0.08), Relative fitting index (greater than 0.9) showed Comparative Fit Index (CFI) = 0.952, Normed Fit Index (NFI) = 0.929, Relative Fit Index (RFI) = 0.916, Incremental Fit Index (IFI) = 0.932, and Tucker-Lewis index (TLI) = 0.943. A reduced fitting index (greater than 0.5) yielded Parsimonious Normed Fit Index (PNFI) = 0.707, Parsimonious Goodness-of-Fit Index (PGFI) = 0.679. This indicates that the urban amenity scale is a three-dimensional global construct, and the relationship between the three factors and 20 measurement items exists and is stable.

2.5 Factors naming

The common factor (F1) contains four items, showing the advantages of jobs and salary levels provided by the city, which accurately reflect the city's work amenity. Therefore, this factor is referred to as an urban work amenity. The common factor (F2) contains five items, showing the ease of access to transportation, medical care, education, and other resources necessary for a basic life in the city, which reflects the amenity of the city in terms of living. Therefore, this factor is referred to as an urban life amenity. The

TABLE 1. Result of exploratory factor analysis

Items	1	2	3	Cronbach's α	AVE	CR	Cronbach's α
There are many public study rooms in the city to facilitate your study	0.822			0.943	0.867	0.925	0.952
The city's libraries provide you with a good learning environment	0.813						
There is a wide variety of specialty bookstores in the city that will attract you to purchase	0.766						
Students' dialogues and discourse in the city are constantly learning or "happening," "tripping," your own learning activities is more sufficient	0.686						
The city or near the city's museums, sports, lakes, forest gardens, ancient ruins, temples, historical sites and other tourism resources are rich, you can travel long and short vacation leisure	0.695						
There are many parks in the city, and it is convenient to picnic and camp on weekends	0.680						
There are many colleges in the city, and the learning atmosphere is strong	0.682						
There are many colleges and universities in the city, and the coverage rate of national examinations is high, which is convenient for you to participate in various examinations	0.678						
The city's sports studios, gym, swimming pool, basketball hall and other sports facilities are available, which is convenient for you to exercise and fitness	0.647						
The city's opera, crosswalk, drama, traditional drama, concert, folk drama and other activities are frequently arranged for you to choose to watch	0.621						
The city's bars, KTV, table games, chess and card rooms and other venues are densely distributed, with large choices	0.575			0.907	0.786	0.876	
The long distance or short distance travel out of the city is convenient, there are many means of transportation to choose from, and it is convenient		0.874					
The city is convenient to travel within the city, subway line, network car coverage in the city is high		0.832					
The city's online and offline shopping experience is good, not only convenient and fast, but also thoughtful, personalized and diversified services		0.811					
The city's catering is full of variety, wide in type, and strong in flavor (the city's internet food restaurants, creative restaurants, attract you to purchase the food experience)		0.762					
The medical conditions in the city make you satisfied, and it is relatively convenient to seek doctor and find medicines and treatment		0.737		0.946	0.876	0.894	
The related industry or occupation of your major has a good development prospect in this city			0.879				
The city offers you a wider space for career advancement			0.832				
The city offers you a wealth of job options			0.825				
The salary level is higher in this city			0.766				

common factor (F1) contains eleven items, showing the city's amusement facilities, leisure venues, learning spaces, and other amenities, which reflect the city's cultural and educational amenities. Therefore, the factor is named urban cultural and study amenity. To sum up, urban work amenity refers to the city's ability to provide high-quality employment opportunities and a favorable economic environment. Its connotation for college youth includes promising career paths, competitive salaries, a strong industrial base, and a dynamic job market. Urban life amenity refers to the ease and quality of daily living. Its connotation encompasses the accessibility and quality of practical necessities such as public transportation, healthcare, housing affordability (as noted in our limitations), safety, and retail services. Urban cultural and study amenity (renamed) refers to the city's provision of assets that enrich intellectual, cultural, and leisure life. Its connotation for college youth is a city that is not just a place to work and live, but also a place to learn, explore, and enjoy a stimulating lifestyle.

3 Research hypothesis

As a measuring tool, the urban amenity scale should possess some common characteristics similar to those of other scales; otherwise, the development of the urban amenity scale will not have good application value. Therefore, it is necessary to develop a relevant model to test the application value of the scale further. This study will explore the impact of urban amenities on the willingness of college youth in first-tier cities to stay in cities, highlighting the effect of urban amenities in attracting young talent. According to the traditional definition of urban amenity (9, 22), pointed out that urban amenity refers to a series of facilities and services provided by the city that make people feel convenient, which is an immovable "local product" and welfare, and obtaining such "local product" and welfare is one of the basic motivations of population flowing into the city. The root cause of urban development and growth is the vibrant urban life and the

resulting high quality of life, which attracts a diverse range of talents, especially innovative ones. Such cities and regions create an environment for people to exchange and innovate, thereby facilitating knowledge spillover (33). In other words, urban amenity is exactly what makes cities attractive to talent, and it has replaced material and geographical advantages as the main driving force for urban development (4, 6). Schmeitner also pointed out that areas that can attract and retain high quality labor will be more successful in future development, and those areas with a high quality of life and pleasant amenities would attract high-quality labor (34).

According to previous studies, when well-educated and high-quality talents choose to live and work, cities with higher amenities tend to be their first choice, which helps enhance the agglomeration of urban innovation factors and promotes sustainable urban development (33, 36). Scholars in Western developed countries have basically formed a consensus that "urban amenity and working development opportunities are the key elements of talent selection in migrating" (37–39). In recent years, China has been swept up in the wave of rapid globalization, urbanization, and the rise of a knowledge-based economy, and the study of urban amenity has attracted the attention of Chinese scholars. Especially at present, China's economy is in a new stage of transformation, and the role of human capital and knowledge has become increasingly significant (20). As highly educated talents, college youth are important human capital, and they are scarce resources that cities compete for. The willingness of young people to stay in the city where they are studying may be influenced by the amenities of that city. First of all, young people in colleges will consider the convenience of cities more or less when choosing jobs, because cities with high-level amenities are easier to attract enterprises to settle down, and thus retain young talent (23). Therefore, the urban work amenity of this city will affect the willingness of college youth to stay in the city. Second, with the improvement of income and education level, people's demand for urban commodity markets, services, beautiful buildings, safe living environment, convenient transportation, and other infrastructure is increasing day by day (8). Moreover, college youth tend to concentrate in cities with high artificial convenience (23). Therefore, the life amenities of the city will also affect the willingness of college youth to stay in the city to a certain extent. Third, American scholar Florida believes that cities attract talents not only by sufficient economic opportunities, high-paying jobs, and rich material convenience facilities, but also by intangible amenities such as inclusiveness, diversity, and openness (23). The People's Daily (Chinese official media newspaper) has also summarized the reasons why Chinese young talent "flee back" to Beijing, Shanghai and Guangzhou, including the openness of big cities, more leisure places in big cities (such as cinemas, theaters, cultural centers, gyms and so on), and the inclusiveness of big cities gathering more young people with similar values. Therefore, the

TABLE 2 Cronbach's α value, CE value, square root of AVE and correlation coefficient of each factor.

Category	F1	F2	F3
Common factor 1	0.487		
Common factor 2	0.337***	0.38	
Common factor 3	0.344***	0.330***	0.42
Square root of AVE	0.705	0.702	0.619
Construct α	0.942	0.89	0.896
CE	0.805	0.87	0.889

*** $p < 0.001$. Diagonal value is factor average variance extracted (AVE) value.

TABLE 3 Comparison of fitness statistics for factor models.

Detection index	Absolute fit index			Relative fit index				Reduced fit index	
	CMIN/DF	RMSEA	NFI	CFI	RFI	IFI	TLI	PNFI	PGFI
Three-factor model	2.024	0.076	0.929	0.932	0.916	0.932	0.946	0.787	0.479
Two-factor model	8.326	0.166	0.807	0.808	0.807	0.808	0.803	0.758	0.446
Single-factor model	12.713	0.194	0.779	0.737	0.664	0.738	0.698	0.626	0.401

The two-factor model combines items of common factor 2 and common factor 3, while the single-factor model combines items of all common factors.

amenity of culture and study in the city will also affect the willingness of college youth to stay in the city.

Based on the above analysis, the following hypotheses are proposed in this study:

- H1a: Urban amenity can significantly affect the willingness of college youth in first-tier cities to stay in cities.
- H1b: Urban work amenity can significantly affect the willingness of college youth in first-tier cities to stay in cities.
- H1c: Urban life amenity can significantly affect the willingness of college youth in first-tier cities to stay in cities.
- H1d: Urban cultural and study amenities can significantly affect the willingness of college youth in first-tier cities to stay in cities.

4 Research design

4.1 Research object and data source

The data used in this study are based on a random sample survey. In March 2023, an online questionnaire survey was conducted among youth from the local colleges in the four first-tier cities of China: Beijing, Shanghai, Guangzhou, and Shenzhen. The term "first-tier cities" is a common classification in China referring to the most economically and culturally advanced metropolises, and the classification is widely used in Chinese academia, media, and official reports (the classification is based on indicators like gross domestic product (GDP), population size, and so on). In the process of collecting questionnaires, we emphasized to the interviewers that the academic research questionnaires require filling in anonymously, and the results of the questionnaire would also be kept confidential. The questionnaires can only be filled in and submitted once, and they cannot be modified after submission. The selection of cities in the survey is mainly based on the following considerations: First, the above four cities are the most typical first-tier cities in China, and their economic, social, and cultural development is relatively better than that of the other cities. Discussions on their urban convenience will be more representative. Second, the above four cities are also gathering places for Chinese universities, and more youth study in these four cities. Examining the willingness of college youth in these four cities to stay in cities is also of great significance for predicting future urban development. The survey's contents include individual characteristics, social interactions, subjective evaluations of urban convenience, and willingness to stay in the city. After removing missing value samples and invalid questionnaires, 235 valid samples were finally collected (descriptive statistics are presented in Table 4). Among them, 194 college youth expressed their willingness to stay in the city, accounting for approximately 78% of the total sample, which indicates that the college youth group has a strong willingness to stay in first-tier cities.

4.2 Variable description and research method

Dependent variable: The dependent variable of this study is the willingness of college youth in first-tier cities to stay in cities, which is

TABLE 4 Descriptive Statistics

Variable	Obs	Min	Max	Mean	SD
Gender	235	0.000	1.000	0.528	0.500
Age	235	0.000	4.000	2.031	0.997
Education	235	1.000	3.000	1.654	0.626
University category	235	1.000	4.000	2.357	1.280
Marriage	235	1.000	4.000	1.280	0.871
City	235	1.000	4.000	2.343	0.899
Social network	235	1.000	7.000	3.503	1.400
Urban amenity	235	1.000	5.000	4.004	0.740
UA	235	1.000	4.000	4.531	0.497
WUA	235	1.000	3.000	4.179	0.671
LA	235	1.000	3.000	4.196	0.603
Williness to stay in cities	235	0.000	1.000	0.769	0.423

UWA, urban work amenity; UA, urban life amenity; WUA, urban cultural and study amenity; LA, urban amenity

measured by the question, "Are you willing to stay in this city after graduation?" in the questionnaire. The answers included "yes" and "no."

Independent variable: The key independent variable is urban amenity, which is measured by the scale developed in this study, including urban work amenity, urban life amenity, and urban cultural and study amenity.

Control variable: In comparison to previous studies, this study selects relevant control variables from the aspect of individual characteristics and social interaction. The individual characteristics mainly include the respondents' gender, age, education level, and marital status. Social networks and social identity will both affect the settlement intention of new immigrants [24]. Similarly, in this study, variables related to social network and social identity are uniformly classified as social relations and included in the control variables.

The decision of college youth on their willingness to stay in a city is a binary problem. According to the willingness to stay in a city, there are two choices: "yes" and "no" with values of "1" and "0" respectively. Therefore, a binary logit model was employed in this study. This model is appropriate for a dichotomous dependent variable and is widely used in similar migration intention studies. The logit model was preferred over the alternative probit model primarily because its coefficients can be interpreted intuitively as odds ratios, which simplifies the discussion of results.

5 Result analysis

5.1 Reliability and validity test

In view of the fact that urban amenity is measured on a 5-point Likert scale, it is still necessary to test the reliability and validity of the data. First, Statistical Package for Social Sciences (SPSS) version 22.0 was used to conduct an exploratory factor analysis on the

TABLE 3 Correlation analysis, reliability and validity test of each variable

Variable	UWA	ULA	UCSA
Urban work amenity	0.793		
Urban life amenity	0.248***	0.907	
Cultural and study amenity	0.279***	0.302***	0.749
AVE	0.629	0.822	0.561
CR	0.87	0.902	0.833
Cronbach's α	0.886	0.888	0.933

Diagonal values denote average variance extracted (AVE) value
 *, **, and *** respectively represent $p < 0.1$, $p < 0.05$, and $p < 0.01$.

urban amenity data, and the KMO value was 0.925 (higher than 0.7). Bartlett's sphericity test found $p < 0.001$, indicating that it is suitable for factor analysis. Second, the reliability test was conducted. The results showed that the Cronbach's α coefficient values for urban work amenity, urban life amenity, and urban cultural and study amenity were 0.886, 0.889, and 0.933, respectively (all higher than 0.7, see Table 3). It is shown that the scales of these three variables had passed the test of internal consistency reliability. The Cronbach's α coefficient for the total scale comprising three variables was 0.946, indicating that the overall structure design of the scale used in this study was highly reliable. Then, AMOS 24.0 was used to conduct confirmatory factor analysis on the recovered data. Each variable was established from a single-factor model to a three-factor model, with fitting and comparison carried out. The results show that the values of CFI, TLI and IFI in the three-factor model are 0.918, 0.905, and 0.919 (higher than 0.9), respectively, RMSEA is 0.086 (close to 0.08), χ^2/df is 2.891 (less than 3), and the fit index of the three-factor model is much better than that of other factor models, which achieved a high standard. This shows that the model fits well. Finally, the validity analysis results show that the AVE value of each variable is higher than 0.5, and the CR value is higher than 0.8, indicating that the scale exhibits good convergent validity. Moreover, the square root of the AVE value of each variable is higher than its correlation coefficient with other variables, indicating that the scale has good discriminant validity.

5.2 Common method bias test

In this study, Harman's single factor test was used to test the Common method bias between variables. Results showed that there were four factors with an eigenvalue of more than 1, and the total variance interpretation was 71.1%. The variance interpretation of the first principal component was 25.8%, less than half of the total variance interpretation. Thus, common method bias was not a significant issue in this study.

5.3 Logit regression analysis

We assessed potential multicollinearity among the independent variables by calculating the Variance Inflation Factor (VIF). All VIF values were significantly below 5 (mean VIF = 1.86), indicating that multicollinearity is not a concern for the robustness of our model

estimates. Then, SPSS software was used to carry out logit regression in this study. Taking control variables as the basic model, four variables—urban work amenity, urban life amenity, urban cultural and study amenity, and urban amenity as a whole—were added to the model to obtain five models, respectively. The analysis results of the models were shown in Table 4.

According to model 1, the control variables of gender, age, education level, university type, and marital status have no significant impact on the participants' willingness to stay in the city. The variable of the city where the college youth live has passed the significance test at the 10% level in the model, indicating that compared with college youth in Beijing, those in other first-tier cities have a stronger intention to stay in the city. That is, compared with the college youth in Beijing, the willingness of college youth in other first-tier cities to stay in the city has increased by 1.382 times. The social relation variable passed the significance test at the 5% level in the model, indicating that when college youth's friends are local residents, their willingness to stay in the city is stronger. That is, compared with the college youth whose friends are not local residents, the willingness of college youth whose friends are local residents to stay in the city is increased by 2.248 times.

Model 2 shows that urban work amenity has passed the significance test at the 10% level ($B = 0.383$, $p < 0.1$), indicating that the higher the urban work amenity, the stronger the willingness of participants to stay in the city. Compared to the urban work amenity at a low level, the higher urban work amenity increases the willingness of college youth to stay in a city by 1.467 times. Therefore, hypothesis H1a is verified. Model 3 shows that urban life amenity has passed the significance test at the 5% level ($B = 0.417$, $p < 0.05$), indicating that the higher the urban life amenity, the stronger the willingness of participants to stay in the city. Compared to the urban life amenity at a low level, a higher urban life amenity increases the willingness of college youth to stay in a city by 1.518 times. Therefore, hypothesis H1b is verified. Model 4 shows that the urban cultural and study amenities have passed the significance test at the 5% level ($B = 0.624$, $p < 0.05$), indicating that the higher the urban cultural and study amenities, the stronger the willingness of participants to stay in the city. Compared to the urban cultural and study amenities at a low level, the higher urban cultural and study amenities increase the willingness of college youth to stay in a city by 1.867 times. Therefore, hypothesis H1c is verified. Model 5 shows that the overall urban amenity has passed the significance test at the 5% level ($B = 0.627$, $p < 0.05$), indicating that the higher the urban amenity, the stronger the willingness of participants to stay in the city. Compared with urban amenity at a low level, the higher urban amenity increases the willingness of college youth to stay in a city by 1.873 times. Therefore, hypothesis H1 is verified.

6 Conclusion and discussion

Based on the urban amenity theory, this study discusses the impact of urban amenities in China's first-tier cities on the willingness of college youth to stay in the city. This study first develops an urban amenity scale based on subjective cognition and evaluation of urban residents, and then establishes a binary logit regression model. Through an online questionnaire survey, first-hand data were collected to verify the model, and the main

conclusions are as follows. The measurement of urban amenity can be divided into three dimensions, namely, urban work amenity, urban life amenity, and urban cultural and study amenity. Urban amenity positively affects the willingness of university students to stay in the city. Specifically, urban work amenities, urban life amenities, and urban cultural and study amenities all have a positive impact on the willingness of university students to stay in the city. In terms of control variables, the cities of college youth and the places of origin of their friends have a significant impact on their willingness to stay in the city.

Summarizing previous studies, it is found that the measurement of urban amenity is an objective indicator, which is supported by the literature of many studies. At the same time, considering the availability of objective data, the measurement of urban amenity by objective indicators can indeed gain the favor of most scholars. However, urban amenity largely depends on people's subjective cognition and judgment (1). The urban amenity, as measured by objective indicators and data, is insufficient in terms of subjectivity. The urban amenity scale developed in this study, which mainly focuses on residents' subjective judgment and evaluation, makes up for the lack of subjectivity of the existing measurement index system to a large extent, and introduces a new dimension of urban amenity, which is a breakthrough and improvement of the measurement index of urban amenity. The conclusion of this study aligns with the findings of Florida et al. (15). In the context of a knowledge-based economy, innovative talents, also known as the "creative class," have a strong demand for urban amenities. Take China as an example, the main source of the so-called "creative class" is university students in first-tier cities, and their cognition and judgment of the urban amenities have actually affected their willingness to stay in the city (16).

This study finds that urban amenity positively affects the willingness of university students in first-tier cities to stay in the city. That is, the higher the level of urban amenity, the stronger the willingness of young college students to stay in the city. After graduation, college youth become a highly educated labor force, which is the core carrier of human capital (7). They are fought over by major cities, which can be seen from the "war for talent" in major cities in China. As the driving force of urban growth, urban amenity does not directly affect urban development, but makes cities more attractive to talent (25). Over the past decade, several studies on urban amenity in the Western context have shown that it has become an essential factor in attracting talent to cities (13, 16). For example, Dalmazio and de Blasio conducted an empirical study using the household income and wealth survey data of the Bank of Italy and found that urban amenity has a strong attraction on the labor force with higher education (26). An empirical study on urban amenity in the Chinese context also shows that cities with higher amenity meet people's needs better; thus, these cities tend to become talent attraction centers. Moreover, the correlation between urban amenity and talent is more significant, which further indicates that urban amenity is more attractive to talent (27). Therefore, the findings of this study show a pronounced effect of cultural and study amenities, challenging any assumption that non-economic factors are secondary in developing countries. This suggests that the preferences identified by Florida may be increasingly universal among the globalized, highly educated youth. Moreover, the findings of this study add nuance to the global literature by demonstrating that for Chinese college youth, amenities are not a

replacement for economic concerns but a complement. The significance of all three dimensions of amenity shows that Chinese talents seek a "complete package," it means a city that offers strong career prospects (work amenity), a convenient and stable daily life (life amenity), and opportunities for personal enrichment and social belonging (cultural and study amenity). Western studies often highlight a tension between economic and cultural drivers, our results from China suggest a more integrative model.

The study further found that the three dimensions of urban amenity—urban work amenity, urban life amenity, and urban cultural and study amenity—all positively affect the willingness of college youth in first-tier cities to stay in the city, that is, the higher the amenity of these three aspects, the stronger the willingness of youth to stay in the city. Moreover, by comparing the odds ratio of college youth's willingness to stay in the city in first-tier cities, it is found that urban cultural and study amenity has the greatest impact on the willingness of college youth to stay in the city, second is urban life amenity, and the last is urban work amenity. Previous studies have emphasized that good educational resources, medical resources, recreational resources, and cultural and artistic services provide an amenity living environment for people, which improves the attraction of cities to the labor force, especially the highly educated labor force (5). Relevant studies by Chinese scholars emphasize the impact of basic public services and find that cities with higher quality of basic public services are more likely to attract population inflows (2, 28). For enterprises, to attract and retain talent, they need local governments to provide urban amenities such as complete infrastructural facilities and public services (2). This practice was early promoted by the early 20th-century Mayor of Birmingham, Chamberlain (who later became Prime Minister of the United Kingdom), who actively promoted municipal reform, advocated government intervention in the livelihood of the people, and provided public welfare in the city (29). After the Industrial Revolution, an urban renovation movement was initiated in Western countries, and it improved the work and living environment of the lower class, represented by the working class, which was largely driven by humanitarian reasons and a desire to guard against socialist shocks. The supply of urban public welfare has facilitated policy diffusion worldwide because of its rationality (30). The concept of "collective consumption" proposed and demonstrated by Manuel Castells, a Spanish Marxist urban theorist, is a theoretical explanation for this phenomenon (31). Since the 1980s, after the great transformation from materialism to post-materialism, some measures of urban amenity, which are based on the urban management strategy to attract the "creative class," have gradually become universal. What's more, this study ranks the attractiveness of urban work amenities, urban life amenities, and urban cultural and study amenities to young talent in college, which can be interpreted as that more chances and convenient access to urban entertainment places can help alleviate the academic pressure and future work pressure of college youth.

7 Policy implications

On the one hand, it is necessary to focus on the study of the micro-urban environment. Because urban amenity depends on people's feelings and cognition to a certain extent, and people's

activities are more closely related to the micro-space of daily life. The study on the amenity of urban micro-environments also helps to better design urban communities and create a more effective urban space that meets people's needs. On the other hand, China's economy is in the transition stage from manufacturing to knowledge-intensive industries, and the demand for highly educated labor will continue to increase in the future. Additionally, with the change in consumption concept and the improvement of income level, people's requirements for quality of life will continue to increase. Therefore, in terms of "attracting talents," in addition to the traditional favorable policy like economic subsidies and lowering the threshold for giving municipal citizenship, in the long run, the key to attracting and retaining talents is to establish a viable labor market. At the same time, it is necessary to pay attention to improving urban quality by enhancing the configuration of public service facilities related to culture and education. Specifically, the government could provide subsidized access to museums, art galleries, theaters, and public sports facilities for youth. Funding and supporting independent bookstores, live music venues, art incubators, and innovation workshops that create a vibrant and authentic urban culture, which is particularly attractive to young people. These are the near-term, high-feasibility measures (highest priority), which face lower barriers to entry and can yield relatively quick wins. Second, the government could develop more affordable housing options for young talents or provide housing vouchers for recent graduates to alleviate their housing pressure. These are the medium-term, foundation measures, and we regarded them as the critical but more complex challenge. Third, the government could attempt to cultivate a dynamic and innovative industrial ecosystem and further improve the management system for responding to demands. On the one hand, it can provide more public services in the field of culture and art for youth, promoting urban amenity and the development of a pioneering cultural and artistic city. On the other hand, it also ensures that young people can have a better experience when accessing public services in the field of culture and art. These are all long-term and systematic measures, focusing on optimizing the overall urban construction.

8 Research limitations

The influence of urban amenity on the willingness of college youth talents to stay in the city is a complex issue involving multiple factors, which deserves in-depth research and exploration. Although this study attempts to be rigorous and standardized in its theoretical derivation and empirical test, it still has the following deficiencies due to limited research experience and resources. First, in terms of data, this study is based solely on the sample data of a random sampling survey, and the sample size is not large enough, which may lead to bias in the research results. The data have passed the reliability and validity tests, as well as the common method bias test. However, future studies can further expand the sample size to improve the reliability and validity of the study. Second, in terms of control variables, the omission of a socioeconomic variable (such as parental income or family wealth) is a substantial limitation. Given that housing affordability is arguably the single greatest barrier to long-term settlement in first-tier cities, this omission means our model cannot account for a major source of variation in retention

willingness. This likely leads to an overestimation of the net effect of amenity for a significant portion of the population. We strongly recommend that future studies prioritize the inclusion and analysis of such covariates. Third, in terms of the generalizability of our findings, they may be limited by the unique context of Chinese first-tier cities. These cities represent an extreme case of economic development, high living costs, and intense competition. The relative importance of work, life, and cultural amenities likely varies across different city tiers and cultural contexts. Generalizing the findings requires caution, and future comparative research across different city tiers and national contexts is needed to build a universal theory. Furthermore, our findings must be interpreted within the unique institutional context of China's Household Registration (Hukou) system. While our "urban life amenity" dimension captures perceptions of healthcare and other public services, access to these services, especially in first-tier cities, is often contingent upon obtaining a local Hukou. The high cost of living and the difficulty of acquiring a Hukou in cities like Beijing and Shanghai present a formidable structural barrier that may attenuate the positive relationship between amenity perceptions and retention willingness (33). Future research should explicitly integrate Hukou-related variables to disentangle the complex interplay between soft amenities and hard institutional constraints in shaping the futures of China's educated youth.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZC: Conceptualization, Writing - review & editing, Writing - original draft, Supervision, Funding acquisition, Resources, Visualization, Data curation. (L: Methodology, Writing - review & editing, Conceptualization, Validation, Investigation, Resources, Writing - original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Chen E, Chen N, Shi L, Hu H, Zeng Y. Spatial differences and influencing factors of migrant talents' residence intention from the perspective of content: a case study of the Yangtze River Delta urban agglomeration. *Eur. Asian J. Soc. Sci.* (2023) 37:22–36. doi: 10.19675/2474-1014/20230019
- Zhang Y, Yu Z, Hu Z, Chen C. The effects of urban complexity, economic opportunities and urban size on the spatial distribution of highly educated labor force in China. *Top. Geogr.* (2021) 41:245–55. doi: 10.13294/j.tgkx.2020.003103
- Wu L, Zhang H, Liu B. Research on urban complexity, agglomeration and urban happiness: an analysis based on CGO (2013) data. *Chinese Geogr. Res.* (2022) 32(1):8. doi: 10.19646/j.cnki.11-2576/G2.2022.0003
- Florida R. *Bohemia and economic geography*. *Econ. Geogr.* (2005) 2:59–71. doi: 10.1080/0014180042000166128
- Glaser EL, Kofas J, Sant A. Consumer city. *J. Econ. Geogr.* (2000) 1:27–38. doi: 10.1093/jeg/1.1.27
- Wu T, Cai J, Tang Z, Song T. Review and inspiration of urban complexity research abroad. *Prog. Geogr.* (2024) 43:220–30.
- Urban RL. Regional development and the geography of concentration. *Pop. Reg. Sci.* (1958) 4:179–99. doi: 10.1111/j.1465-2507.1958.tb00296.x
- Betcher WR, Wundtshimide PR. *The economic pursuit of quality*. Newark: New York: M. E. Sharpe (1996).
- Gallardo PD. Amenity as an economic development tool: is there enough evidence? *Econ. Dev.-Q.* (1994) 8:270–83. doi: 10.1177/08912432940080030104
- Jaeger MJ. Quality-of-life differences and urban and regional outcomes: a review. *Asian Policy Debate* (1999) 7:739–77. doi: 10.1080/09737329908839324
- Liu Y, Shen T. Measuring skilled and less skilled interregional migration in China, 1996–2011. *Appl. Spat. Anal.* (2017) 21:2437–44. doi: 10.1016/j.apspa.2017.03.001
- Paul VA, Knox L, Smith DM, Smith DM. *Human geography: a welfare approach*. London: Edward Arnold. *Prog. Hum. Geogr.* (1991) 15:389–94.
- Wu SC. Urban complexity, quality of life and urban development: a review and enlightenment. *Urban Plan. Forum* (2018) 471–5.
- Christensen BSK. *Making business location decisions*. London: Longman Higher Education (1992).
- Florida R, Mellander C, Rodrik D. Inside the black box of regional development: human capital, the creative class and tolerance. *J. Econ. Geogr.* (2008) 8:615–40. doi: 10.1093/jeg/8.4.615
- Mullander C, Florida R, Rodrik D. The creative class, post-industrialism and the happiness of nations. *Geogr. J. Reg. Dev. Sci.* (2012) 5:33–43. doi: 10.1080/09697580.2012.651296
- Diwanji H, Barnidge SD, Galloway J. Do coastal amenities attract high-tech jobs? Evidence from a smoothed Bayesian spatial model. *Appl. Econ. Anal.* (2011) 6:395–412. doi: 10.1080/17447722.2011.603811
- Garrison H, Mollen U. *Amenities and the attraction of Dutch cities*. *Erg. Stud.* (2015) 51:324–36. doi: 10.1080/00140139.2015.1035299
- Khoo SE, McDonald P, Vuong QH, C. Hogg G. A global labor market: factors increasing the sponsorship and temporary migration of skilled workers to Australia. *Int. Migr. Rev.* (2007) 41:689–710. doi: 10.1111/j.1747-7379.2007.00296.x
- He J, Song C. Dynamic mechanism of creative industry agglomeration driven by urban complexity: a case study of Nanjing brand design industry. *Econ. Geogr.* (2019) 39:134–142. doi: 10.13390/j.cnki.jgl.2019.03.019
- Lin J, Tang Y, Luo H. The relationship between urban complexity, difference and innovation ability in Beijing. *Acta Geogr. Sin.* (2022) 42:115–25. doi: 10.13282/j.cnki.aps.2022.03.011
- Nichols CT. Office amenities, labor, space, and your home life: does stress development? In: T. Nichols Clark, editor. *The city as an metropolitan machine: Research in Urban Policy*. vol. 5. London: Emerald Group Publishing Limited (2005) 165–82.
- Duan N. Urban complexity, work opportunities and 'flight back to Beijing, Shanghai and Guangzhou' of migrant classes of creative class. *Geogr. Res.* (2022) 2:90–100.
- Liu T, Liu S, Li Z. The settlement pattern of new urban immigrants in China and its influencing mechanism. *Econ. Geogr.* (2016) 36:798–7. doi: 10.13296/j.cnki.jgl.2016.07.007
- Zhang B, Yang X. Study on the impact of urban complexity on urban population growth in China. *Urban Plan. Rev.* (2017) 24:144–50.
- Dalmazzo A, de Biase G. Amenity and skill-based agglomeration effects: some results on Italian cities. *Pop. Reg. Sci.* (2013) 40:309–28. doi: 10.1111/j.1475-2875.2013.00327.x
- Wu T, Cai J, Tang Z, Song T. Urban complexity: a new perspective and empirical study of urban competitiveness evaluation in China. *Geogr. Res.* (2016) 35:214–28. doi: 10.11821/dg.2016031002
- Zhang Y, Song Q. The impact of urban complexity on labor mobility. *China Popul. Resour. Environ.* (2019) 29:218–25.
- Kilpin R. *Industrial location, Enterprise and trading in the Victorian City*. Oxford: Clarendon (1976) 3:30–45.
- Rodgers DT. *Atlantic crossings*. Cambridge, Massachusetts: Harvard University Press (1998).
- Tilly C. *The city and the gateway: A cross-cultural theory of urban social movements*. By Manuel Castells (Berkeley and Los Angeles: University of California Press, 1983. xv plus 473 pp. \$24.95; 756 pp. \$48.00) 19:373–4.
- Gu H, Xiao Z. Reframing the nexus between urban amenities and migrants' labor mobility intentions in China: the role of the labor value. *Economic Geogr.* (2022) 42:642–68. doi: 10.1080/15467214.2024.2379487



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Female-friendly residential facilities and living satisfaction: evidence from Yangpu District, Shanghai

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Introduction: With the acceleration of global urbanization, the development of female-friendly cities has become a key objective in urban planning. This study investigates strategies for optimizing residential community facilities in Yangpu District, Shanghai, from a female-friendly perspective, aiming to inform policymakers and improve the quality of life and satisfaction of women.

Methods: Drawing on field surveys conducted across 36 communities and 923 valid questionnaires, descriptive statistical analysis and structural equation modeling (SEM) were employed to examine women's daily needs regarding safety, convenience, and opportunities for social interaction.

Results: The key findings reveal that, first, the built environment of community facilities significantly influences perceptions of female-friendliness and residential satisfaction, with recreational facilities exerting the strongest impact. Second, the direct relationship between female-friendliness and satisfaction is relatively weak, potentially due to individual differences and variations in environmental contexts. Finally, subjective perception mediates the relationship between the built environment and overall satisfaction.

Discussion: Based on these findings, this study proposes a comprehensive strategy implementing incentive policies and evaluation mechanisms, optimizing spatial layouts, establishing women-specific facilities, and enhancing connectivity, and strengthening facility management and service standards.

KEYWORDS

women-friendly, supporting facilities, residential satisfaction, subjective perception, Yangpu District

1 Introduction

The pursuit of gender equality and inclusive urban development has propelled the concept of "women-friendly cities" to the forefront of global urban planning agendas. With the acceleration of global urbanization, creating urban environments that cater to the diverse needs and safety concerns of women has become a critical goal for sustainable and equitable development (1). This movement recognizes that traditional urban planning often overlooks the distinct experiences and requirements of women in public and residential spaces, potentially leading to inconveniences, reduced mobility, and diminished quality of life (2, 3).

Pioneering efforts, such as Seoul's "Women-Friendly City Plan" launched in 2007 (4) and Vienna's long-standing focus on infrastructure transformation considering women and children's needs since the 1990s (5), exemplify this global trend. In China, Changsha emerged as the first city to explicitly propose building a "women-friendly city" in 2021, prioritizing women's safety through tangible measures like enhanced street lighting and surveillance systems (6). Subsequently, major cities including Hong Kong, Shenzhen, and

Shanghai have also expressed commitments to fostering women-friendly urban environments (7–8). This concept can to a certain extent alleviate gender differences in urban spaces, aiming to integrate women's daily life needs, including safety, convenience, social interaction, health and care, into the design and planning of residential areas, in order to create a safer, more comfortable and more inclusive living environment (8, 20, 21).

However, significant research gaps still exist, especially in the context of China, regarding the subtle mechanisms between the built environment of residential facilities and women's experiences. Specifically, insufficient focus on facility-user relationship. While the importance of women-friendly facilities is acknowledged, empirical research specifically examining how the built environment of community facilities directly influences perceived women-friendliness and, ultimately, residential satisfaction remains relatively scarce, especially at the micro-scale and within the Chinese context (2). Furthermore, limited understanding of subjective perception's role. The potential mediating role of residents' subjective perception between the built environment and overall residential satisfaction, particularly from a gendered perspective, is underexplored. More importantly, heterogeneity of women's needs. Existing studies often treat "women" as a monolithic group, lacking granular analysis of how diverse factors shape distinct facility preferences and satisfaction drivers within residential areas (10).

Therefore, this study aims to explore the role of the built environment of residential area supporting facilities, including transportation, residence, commerce, culture, leisure, etc., in influencing women's perception of friendliness, and ultimately the causal path that affects women's residential satisfaction. Identify and compare the relative attractiveness of different areas and community facilities within the community to women. Examine the specific relationship between female residents' perception of female-friendliness and overall residential satisfaction. To explore the mediating role of subjective perception between facility environment and residential satisfaction. Taking Yangpu District of Shanghai as an example, evidence-based strategies for strengthening female-friendliness in urban residential area planning and facility provision in China are proposed.

Yangpu District in Shanghai has become an ideal research case due to its unique historical heritage, economic vitality, large female population, diverse family structures, diverse urban structures (coexistence of old and new communities), and relatively developed transportation infrastructure. This diversity provides a solid research basis for studying the subtle needs of different women groups and the effectiveness of existing facility regulations (42).

This study theoretically deduces the understanding of the complex connection between the built environment of facilities and female-friendliness, subjective perception, and residential satisfaction through clear modeling and empirical testing. In terms of methods, a strict mixed approach is adopted, especially centering on the perspectives of women from different communities in major Chinese cities. New insights have emerged into the relative importance and appeal of different types of facilities to women. The research findings can provide evidence-based guidance for urban planners and decision-makers to optimize living facilities, enhance women's safety and satisfaction, and build fair and women-friendly cities. Overall, this study provides an empirical basis for transforming the concept of female-friendly cities into practical improvements in women's daily living.

2 Literature review

2.1 Residence satisfaction

With the acceleration of urbanization, the construction of community public facilities has become one of the important indicators to measure the quality of urban development. Existing literature indicates that community public facilities are an important factor influencing residential satisfaction, and there is a close theoretical connection between their construction level and the quality of residents' lives (13–17). Wells and Yang (16) et al. found that well-designed public facilities can encourage residents to walk, increase physical activity, and enhance social interaction among residents during walking, thereby positively influencing residential satisfaction. A large amount of survey data further reveals that the completeness of infrastructure, the accessibility of public service facilities, and the diversity of recreational facilities are all significantly positively correlated with residential satisfaction (15, 17).

It is worth noting that residents' demographic characteristics such as age, education level, and family income play a moderating role in the relationship between public facilities and residential satisfaction, and different characteristic groups have obvious differences in their demand preferences and satisfaction perceptions of public facilities (12, 14). However, most studies treat the community as a whole and do not fully consider the heterogeneity of different areas within the community. In addition, large-scale comparative studies across regions and multiple communities are relatively rare, which is not conducive to summarizing the general laws and special cases of the relationship between public facilities and residential satisfaction in different regional contexts. Therefore, in the process of continuous advancement in the construction of community public facilities, a deeper understanding of the complex relationship between them and residential satisfaction is of great academic value and practical guiding significance for optimizing community planning and improving the quality of residents' lives.

2.2 Female friendliness

The concept of female-friendliness is grounded in environmental psychology and gender-sensitive urban planning theories, which emphasize that a female-friendly environment must address both objective safety and subjective comfort (8). In the context of urban sustainability construction, the degree of female-friendliness has received extensive attention. Many scholars have pointed out that a female-friendly community is reflected in multiple aspects (18–23).

Firstly, the advancement of urban planning can help improve women's safety. It is necessary to conduct human-scale design based on the diverse needs of women, provide more public spaces and community facilities, and increase the breadth and depth of women's activity spaces, such as well-lit streets and mother-and-baby rooms, which can enhance the safety of the city and increase women's sense of security (18, 20). Night lighting is operationalized as an indicator of female-friendliness because it directly influences women's perception of safety during evening activities (19). However, current research on spatial planning lacks quantitative studies on how to accurately measure the specific needs of women in different regions for the breadth and depth of activity spaces, resulting in low utilization rates of some facilities in actual use.

What's more, community services should cover projects such as women's vocational training and mental health counseling, and enhance women's sense of community belonging through various activities to support their self-development and social integration (21). However, existing women's vocational training and mental health counseling projects are lacking in terms of service continuity and targeting, and the special needs of women of different ages and social strata have not been fully met.

In addition, the government encourages women to participate in community decision-making and guarantees their right to speak in community affairs, ensuring that community construction fully considers the female perspective (18). However, the design of specific participation mechanisms is not perfect, and there is a lack of effective supervision and feedback mechanisms to ensure the true implementation of women's right to speak.

Therefore, building a female-friendly urban community is an important foundation for achieving sustainable urban development and social harmony.

H1: The friendliness of women in the community has a significant positive impact on residential satisfaction.

2.3 Facility built environment

Community facility construction is a key element in enhancing the quality of life for residents and promoting community development, attracting in-depth research from scholars in various fields (22–26). The suitability of public facilities not only depends on residents' needs and the convenience of use but also on the operational efficiency and maintenance costs of the facilities themselves. Latham and Layton (24) and others pointed out that social infrastructure in cities (libraries, parks, commercial places, transportation facilities etc.) is crucial for public life, as it promotes social connections and fosters a sense of community belonging. In terms of analyzing the spatial supply capacity of public service facilities, community facilities are classified into three major categories: living services and commercial facilities, cultural and recreational facilities, and public transportation facilities, as the key research objects. Through specific spatial analysis methods, it was quantitatively evaluated that some community living services and commercial facilities are concentrated in the core area, while the periphery is lacking, resulting in significant differences in the convenience of residents accessing daily services (23). Cultural and recreational facilities do not match the age structure and cultural preferences of residents, failing to meet their diverse spiritual and cultural needs (25). The setting of public transportation facilities and the planning of routes do not well connect with and transfer in the hotspots of residents' travel, affecting transportation efficiency and travel experience (26). However, in terms of research depth, there is a lack of in-depth analysis on how the built environment of facilities specifically affects the friendliness toward women, especially at the micro level, such as the impact of facility design details on women's sense of security and comfort.

It is worth noting that the built environment of facilities plays a crucial role in creating a female-friendly space. However, existing research on how to better integrate women into social life from multiple dimensions such as safety assurance, environmental comfort, and inclusive atmosphere is relatively scarce. At the same time, high-quality infrastructure, rich public services, and a good ecological environment

can enhance the convenience and comfort of residents' lives, thereby improving their satisfaction with living; conversely, it can lead to residents' dissatisfaction and lower their satisfaction with living (27).

It should be pointed out that the quality of the built environment of community facilities has a significant impact on residents' subjective perception, the friendliness toward women, and their satisfaction with living to a certain extent. This assumption provides a theoretical basis and research guidance for further in-depth studies on the intrinsic connection between community facility construction and the improvement of residents' quality of life.

H2: The built environment of the facility has a significant positive impact on the friendliness of women in the community.

H3: The built environment of the facility has a significant positive impact on subjective perception.

H4: The built environment of the facility has a significant positive impact on residential satisfaction.

2.4 Subjective perception

In the context of social public facility construction, research on the subjective perception of the public has shown a diverse trend of development (27–29). From the perspective of convenience perception, the satisfaction of public space is closely related to factors such as the convenience of public facilities, which is helpful for exploring the demands of community residents for the convenience of public facilities and the construction of an evaluation system (27). However, existing research lacks perception studies specifically targeting the female group.

Perception of accessibility involves physical distance, ease of access, and cost, which is particularly crucial for vulnerable groups (30, 31). Poor accessibility can lead to social equity issues. Wang et al. (28) found that the urban land accessibility of public service facilities is normally distributed, and the accessibility of different types of facilities varies significantly. Facility type has a significant impact on urban land accessibility, while different towns have no significant impact on the accessibility of educational facilities but have a significant impact on the accessibility of primary medical facilities. However, there is a lack of long-term tracking and evaluation of the effectiveness of accessibility improvement measures, making it difficult to determine whether these measures can continuously meet the needs of residents. Perception of aesthetics plays an important role in shaping the unique image of a city and improving the quality of life of residents. Wang et al. (29) evaluated the quality of the visual environment in communities by using time series street view images, including six perception indicators such as aesthetics and assigning scores. They found that improving the visual environment quality, including community aesthetics, enhances residents' subjective perception and helps the government improve policies. However, existing research lacks unified standards for quantifying aesthetics, resulting in poor comparability of results among different studies.

These subjective perception dimensions are interrelated and jointly reflect the public's attitude and experience toward public facilities, providing a reference basis for the planning, construction, and optimization of public facilities (32). Many studies have deeply analyzed the factors and their influences in each dimension from

different cases and perspectives to enhance the social benefits and public satisfaction of public facility construction.

H3: Subjective perception has a significant positive impact on residential satisfaction.

Through the study of the literature, the following deficiencies were found. Firstly, is there a correlation mechanism between the built environment of facilities and the needs of women? Although most studies recognize the importance of female-friendly facilities, they lack micro-empirical analysis on how the built environment of facilities specifically affects female-friendly perception at the community scale and thereby influences residential satisfaction. Such studies are particularly scarce in the urban context of China. Secondly, whether there are mediating variables between the built environment of the facilities and satisfaction. Most existing studies focus on the direct correlation between the objective attributes of facilities and satisfaction, but rarely explore the transmission effect of residents, especially women's subjective perception, in this regard. Thirdly, the heterogeneity of the needs of the female group has been simplified. Existing studies often view "women" as a single group and fail to adequately analyze the impact of differences such as age, family structure, and income on facility preferences and satisfaction drivers, resulting in limited explanatory power of research conclusions for the diverse needs of women. Therefore, in response to the above questions and deficiencies, this study constructed a theoretical model consisting of five hypotheses to systematically explore the causal relationships among the variables (Figure 1).

3 Research design and methods

3.1 Research site and data source

This study chose Yangpu District of Shanghai as the research site because its unique characteristics make it relevant and typical for

research from a female-friendly perspective. Firstly, in terms of policy relevance, Yangpu District is one of the important areas in Shanghai that is committed to building a "women-friendly city". Secondly, there is a larger female population and the social economy is diverse. This district has a large female population, including a considerable number of working professionals, students and older women, etc. Meanwhile, the diversity of age, occupation, family structure and income level is crucial for capturing the heterogeneity of women's demands and experiences for residential facilities. Secondly, urban form and residential types. Yangpu showcases a unique integration of urban textures, including historical industrial heritage, traditional Shikumen and workers' new villages, as well as modern high-rise residential developments (18). In addition, economic vitality and infrastructure. As a vibrant and revitalized area, Yangpu boasts significant commercial centers, educational institutions, cultural venues and residential areas. Relatively developed transportation infrastructure provides convenience for daily travel. This background reflects the complex interaction between residential facilities and the broader urban functions that shape women's daily lives, safety and convenience.

As shown in Figure 2A, due to the availability of data, this study mainly focuses on 36 residential communities in Yangpu District. The study area is about 198 hectares, the permanent population is about 152,500, and the population density is about 12.98 people/square meter. These communities are selected as research samples because their location in the street is significantly representative and their attribute characteristics are unique, which is convenient for in-depth exploration of the relationship between residents' demand and the supply of public facilities space. As shown in Figure 2B, the schematic diagram of the planned land use for public facilities in Yangpu District is presented. From the perspective of spatial layout, the core community and the fringe community have different needs for transportation and other facilities. In terms of population structure, communities dominated by young groups and older children have obvious differences in demand for entertainment, fitness, senior support services, education and other facilities. The obvious difference

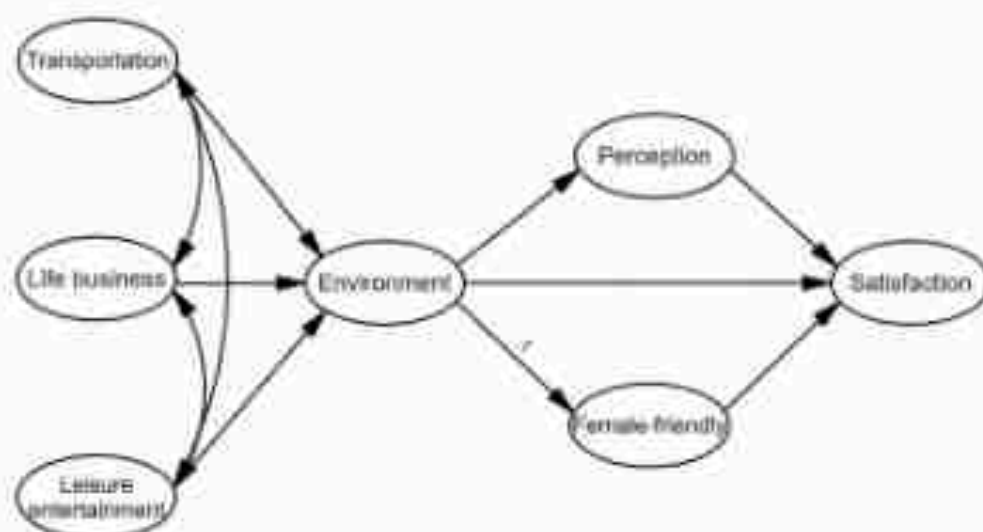
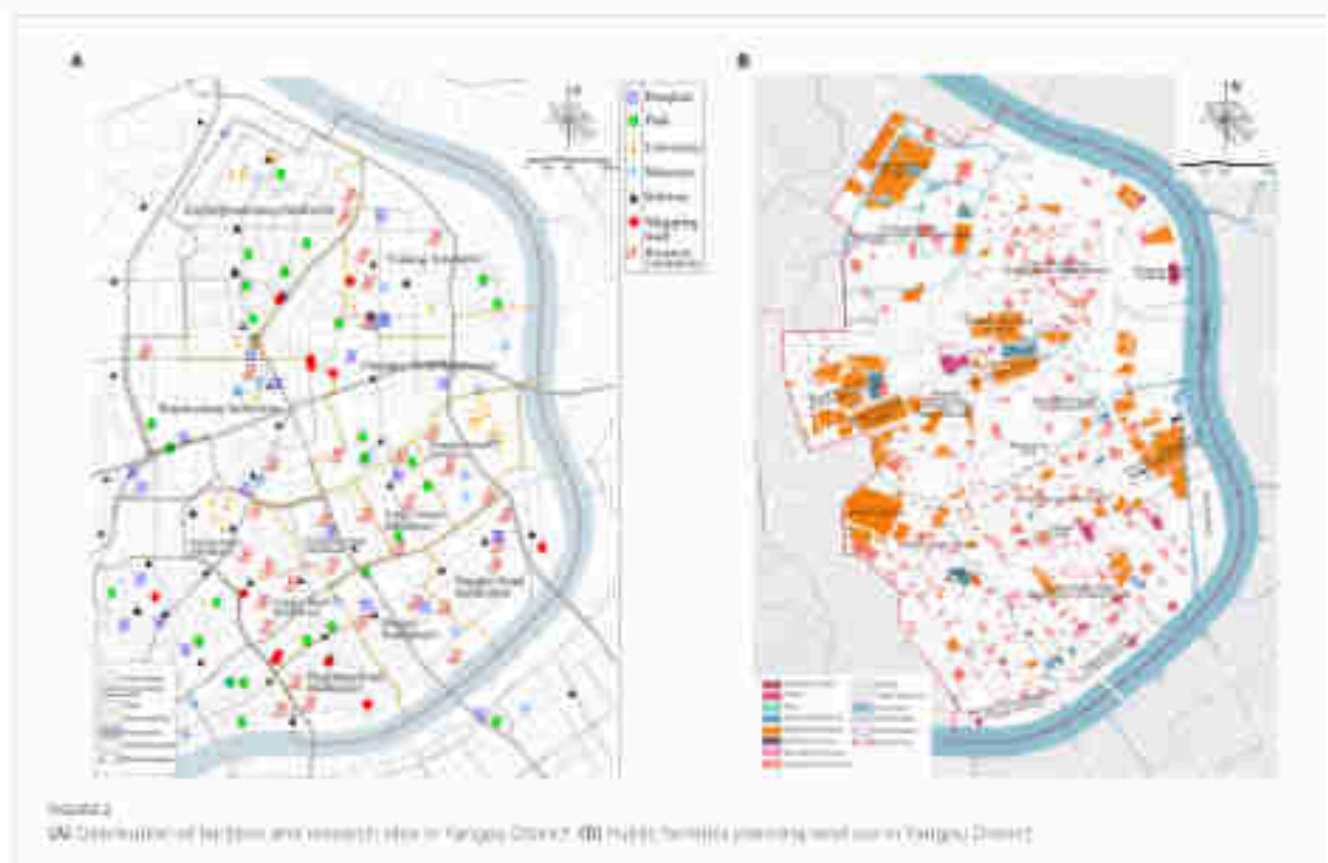


Figure 1
The structural model assumed the path.



between these communities and other areas in the street in all aspects has significant and special value for studying the matching degree and gap between residents' demand and public facilities supply.

A total of 968 questionnaires were distributed in this survey, and 923 valid questionnaires were retrieved, with an effective rate of 95.4%. The questionnaires mainly covered multiple aspects such as environmental factors in residential areas, the current usage and satisfaction of public service facilities, and the demand for types of public service facilities. They involved different types of communities and people of various age groups within the research scope, with an average age of 33.95 years. This sample size is sufficient for SEM analysis because it exceeds the usually recommended ratio of 10 to 20 observations per estimated parameter [35]. This ensures robust model estimation and reliable hypothesis testing.

3.2 Research methods

This study uses field investigation and questionnaire interview methods, combined with ArcGIS map, POI data and structural equation model (SEM), to deeply explore the matching relationship between the current community residents' demand and the space supply of public service facilities within the research scope, and serves as a reference for the accurate adjustment and optimization of public service facilities in the living circle of community.

IBM SPSS Amos 28.0 software was used to complete the path diagram of the structural equation model (SEM). In addition to direct effects, indirect effects were estimated using the Bootstrap method with 5,000 resamples to assess the mediating role of

subjective perception (SP) between the built environment (BE) and residential satisfaction (RS). The significance of indirect effects was determined by 95% bias-corrected confidence intervals (CIs). Structural equation model consists of two parts: structural model and measurement model. The measurement model represents the correlation between explicit variables and corresponding latent variables, while the structural model represents the potential causality between endogenous variables and exogenous variables. As shown in Figure 2, the structural model is formed by the structural relationship composed of eight measurement models.

Structural equation models are generally represented by three matrix equations:

$$X = \Lambda_x \xi + \delta \quad (1)$$

$$Y = \Lambda_y \eta + \varepsilon \quad (2)$$

$$\eta = \beta \eta + \Gamma \xi + \zeta \quad (3)$$

Equations 1, 2 are measurement models, and Equation 3 are structural models. X is the observation variable of exogenous potential variables, that is, a series of indicators to measure the objective built environment, subjective perception and individual attributes; ξ is the potential exogenous variable; Y is the observed variable of endogenous potential variable; η is the endogenous latent variable; Λ_x and Λ_y are the factor load matrices of the variables X and Y ; β and Γ are both path coefficients; δ is the relationship between

endogenous latent variables. Γ is the effect of exogenous latent variable on the value of endogenous latent variables. ξ is the error term of the structural equations (Table 1).

3.3 Data analysis

Table 1 describes each dependent variable, latent variable, observed variable and variable rules. From the perspective of women, based on the existing evaluation methods of community living satisfaction [34–36], a five-level scale is adopted to comprehensively

consider subjective and objective conditions, and then a structural model is formed.

As far as the built environment of facilities is concerned, the classification standard of community facilities is adopted, which is divided into three categories: transportation facilities, living and commercial facilities, and cultural and leisure facilities. Among them, the walking comfort level (TP1) in the community, the reasonableness of lane design (TP2) and the traffic condition in the living circle (TP3) are the key indicators to evaluate the community transportation facilities (TP). The physical exercise facilities (LF1) set in the community and the commercial (LF2), catering (LF3), medical (LF4)

TABLE 1 Definition of variables

Latent variable	α	Observed variable	Variable interpretation
Individual attribute factors	ID	ID1 Age	Gap filling
		ID2 Educational level	Primary and below = 1 Junior high school = 2 High school/secondary vocational school = 3 Junior college = 4 Undergraduate course = 5 Master = 6 Doctoral scholar = 7
		ID3 Duration of residence	0–4 years = 1 5–9 years = 2 10 years or more = 3
		ID4 Monthly income (RMB)	0 yuan = 1 < 200 yuan = 2 200–3,000 yuan = 3 3,000–10,000 yuan = 4 10,000–30,000 yuan = 5 More than 30,000 yuan = 6
		ID5 Third- or fourth- generation's financial situation	Very poor = 1 Relatively poor = 2 Middle income = 3 Relatively rich = 4 Very rich = 5
Transportation	TP	TP1 Walking comfort	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		TP2 Lane design is reasonable	
		TP3 Life circle traffic convenience	
Living facilities	LF	LF1 Sports exercise facilities	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		LF2 Life circle business environment	
		LF3 Life circle catering environment	
		LF4 Life circle medical environment	
		LF5 Life circle education environment	
Cultural and leisure	CP	CP1 Children's playground in the community	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		CP2 Leisure activities in the community	
		CP3 Cultural activities in community	
		CP4 Living circle leisure environment	
		CP5 Cultural environment of life circle	
Female-friendly	WF	WF1 Child-friendly in community	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		WF2 Female-friendly in community	
		WF3 Life circle child-friendly environment	
		WF4 Night lighting	
Perception	IP	IP1 Property Service Level	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		IP2 Neighborhood	
		IP3 Cell coverage	
Satisfaction	S	S1 Satisfaction in community	Strongly disagree = 1 Disagree = 2 General = 3 Approval = 4 Strongly agree = 5
		S2 Satisfaction in life circle	
		S3 Satisfaction with current living conditions	

and educational (LF5) environments within the living circle play an important role in the evaluation of living and commercial facilities, which profoundly affects the overall perception of female residents on the living environment and the evaluation of life quality (37). At the same time, the construction completeness of children's amusement facilities (CF1), leisure activity venues (CF2) and recreational activities facilities (CF3) as well as the leisure and cultural environment (CF4.3) in the living circle of the community profoundly reflects the degree of concern about the quality of life of residents and the level of comprehensive livability of a community (37). Child friendliness (WF1.3) can confirm the difference in women's perception of the sense of security in the community living environment. Night lighting (WF4) reflects a broader social context, namely care and inclusiveness. Bright streets not only reduce the risk of crime but also enable women to participate in night-time social activities and cultivate a sense of community belonging (1). These factors have a profound and unique impact on women's life experience in the community, especially when they bear the main responsibility of child rearing and face daily travel and social activities (38). The service level of residential properties (SP1), the friendliness of the surrounding neighborhoods (SP2), and the governance situation in the residential community (SP3) greatly affect women's subjective perception of the living environment, and shape their daily life experience and emotional atmosphere (34).

Before starting the statistical analysis, filter outliers in the data by checking for Z-values and missing values to ensure that the results of the statistical test are more accurate. Follow three steps to test the hypothesis. First, a two-step confirmatory factor analysis method was used to evaluate each structure separately and then validate the overall measurement model (39). Secondly, the reliability, convergence validity and discriminant validity of the model are tested to ensure the psychometric properties of the model. Thirdly, the proposed path model is estimated and hypothesis tested.

4 Results

4.1 Sample and reply brief

As shown in Table 2, the majority of respondents (41.7%) were aged between 30 and 39, followed by residents aged between 19 and 29 (20.0%). They are well educated, with just under 75.1% of them having a university degree or above, with the largest number of residents having a bachelor's degree (54.9%). The majority of respondents have lived in their communities for 0–4 years (39.9%), which may be strongly related to the migrant worker base in Shanghai, followed by more than 10 years (32.1%). The salary income of the respondents is mostly between 5,000 and 9,999 yuan (42.3%), followed by 10,000 to 19,999 yuan (35.0%), which may be related to Shanghai's geographical advantages and economic development. In addition, residents' awareness of the level of family economic status shows a strong normal distribution law, and the majority of middle income is 76.8%. These statistics show distinctive characteristics on all sides. Age, education, length of residence and the distribution of wages and income are all consistent. These detailed data accurately reflect the current situation of Shanghai. Economically, the proportion of high income corresponds to its developed degree; in terms of education, the proportion of high education shows its educational advantages, which has been scientifically verified and has high statistical significance.

TABLE 2 Basic information of female residents

Dimension	frequency	%
Age		
18–29	364	20.0
30–39	493	41.7
40–49	226	24.3
Education		
Primary and below	4	0.1
Junior high school	20	1.2
High school/Secondary vocational school	56	4.2
Junior college	142	15.4
Undergraduate	382	54.9
Master	147	19.1
Doctor	19	2.2
Residential time		
0–4 years	369	39.9
5–9 years	258	28.0
10 years and above	296	32.1
Monthly income (RMB)		
0	20	2.4
1–2,299	30	3.1
2,300–5,999	329	35.6
6,000–9,999	392	42.3
10,000–19,999	331	35.0
20,000 and above	63	6.7
Perception of economic situation		
Very poor	8	0.8
Relatively poor	96	10.4
Middle income	398	42.8
Relatively rich	360	38.6
Living rich	12	1.2

TABLE 3 Model fit index

Model	χ^2/df	RMSEA	CFI	AGFI	GFI	TLI	SFI
Index	1.5	0.080	0.93	0.88	0.92	0.93	0.88
Actual	1.708	0.074	0.950	0.973	0.984	0.981	0.960

4.2 Structural equation model

Before investigating the hypothesized relationships among the latent variables, the proposed factor structure is validated using confirmatory factor analysis (CFA). According to the suggestion of Anderson and Gerbing (40), a two-step method was adopted to verify the multi-attribute scale. The first step is to verify the measurement model for each structure, followed by testing the entire measurement model. The combination reliability and validity of structural equation model are acceptable through confirmatory factor analysis. Each

fitting index of the final model is within the acceptable range (Table 1), so the structural equation model hypothesis is accepted. The results of structural equation models designed in this paper are satisfactory, and the chi-square to freedom ratio (χ^2/df) is less than 3. The approximate root-mean-square error RMSEA is less than 0.08, indicating that the model has a good data fit (41). Although the values of GFI, AGFI, CFI and TLI did not fully reach the ideal value, they were all greater than 0.8, which was within the acceptable range. It indicates that the model and data fit well (42) (Figure 1, 4).

As shown in Table 4, at the reliability level, a scale reliability analysis was conducted on the experimental data. The Cronbach's α coefficient of the overall scale was 0.949 (>0.80 threshold), and the single-item α coefficients of all 25 observed variables exceeded 0.80, demonstrating the outstanding internal consistency of the measurement tool (43). At the validity level, dimensionality reduction factor analysis was conducted on the experimental data. The suitability value of KMO sampling was 0.952 (>0.80 , $p < 0.001$), strongly supporting the suitability of the data for factor analysis (44).

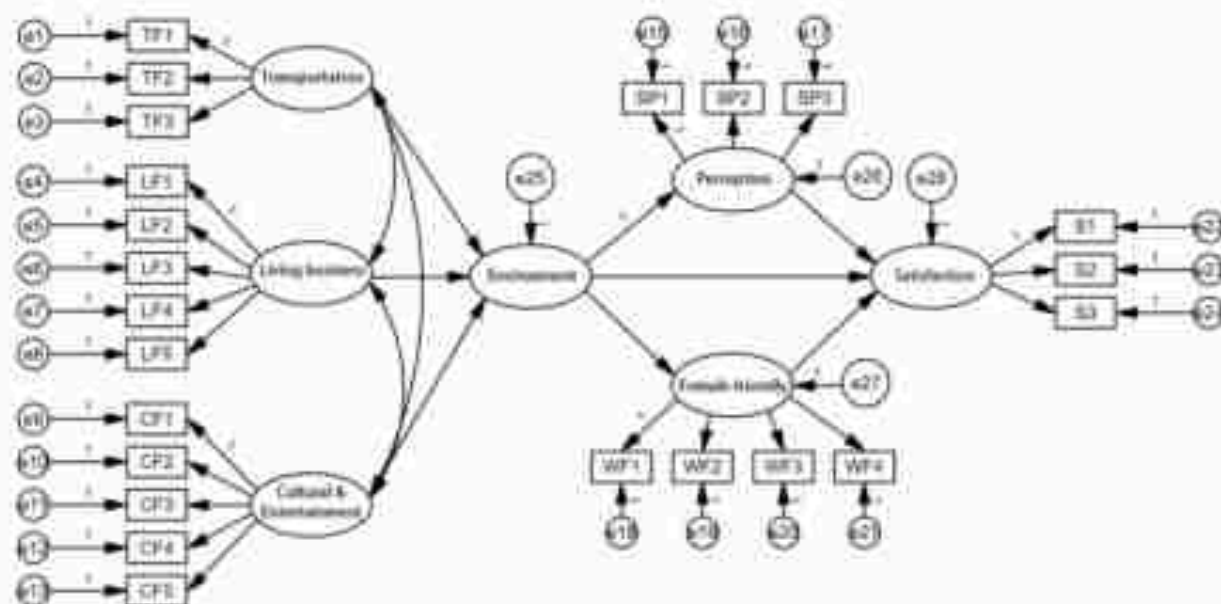


FIGURE 1
Path diagram of the research model.

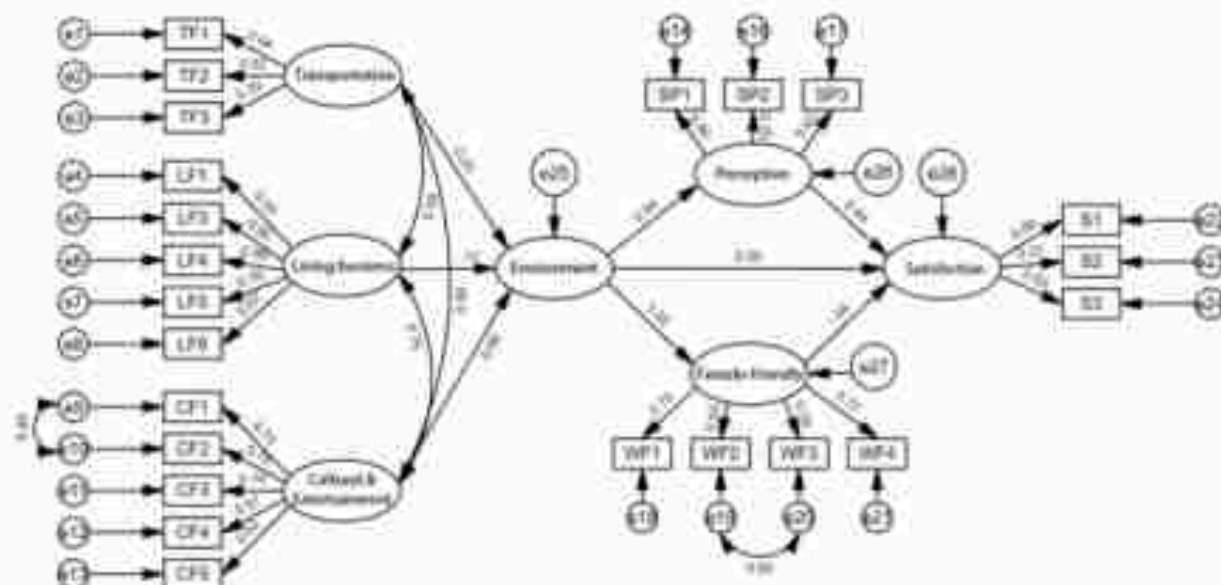


FIGURE 4
Path coefficients of each path in the research model.

4.3 Analysis of influencing factors of facility/life satisfaction

As shown in Table 5, the research found that the overall satisfaction of female residents with the community (S1) was 3.76, which is greater than the median value of 3. This result indicates that female residents generally consider their living conditions to be "fairly satisfactory" from the perspective of sample distribution. "Strongly agree," "Agree," "General," "Disagree," and "Strongly disagree" accounted for 24.1, 39.1, 29.0, 4.7%, and only 3.1%, respectively. The standard deviation of the overall satisfaction within the community was 0.972, indicating that the choices of most female residents were similar. Meanwhile, the overall satisfaction of female residents with the living circle (S2) was 3.83, slightly higher than that within the community, suggesting that female residents are more satisfied with the environment within the living circle than that within the community. Therefore, in terms of the overall satisfaction of female residents, they are generally satisfied with the overall environmental quality of the community.

Regarding the degree of female-friendliness (WF3), female residents' perception of this aspect within the community was relatively poor at 3.19, with a standard deviation of 0.958, indicating that the views of the respondents were relatively concentrated but not completely uniform. Thus, in terms of the current infrastructure in Yangpu District, the degree of female-friendliness is not high. Urban builders and decision makers can take this as a starting point to enhance the overall satisfaction of female residents with their living environment. At the same time, the concept of child-friendly communities regards child-rearing as a shared social responsibility, breaks the traditional constraints on women, changes the social perception of the roles of men and women in child-rearing, enhances women's social status, and promotes the improvement of the degree of female-friendliness. The research found that the degree of child-friendliness within the living circle (3.41) was higher than that within the community (3.27), indicating that there is still potential for child-friendliness within the community to be explored. Finally, night lighting (WF4) can reflect female residents' experience of community safety from the side. Adequate lighting can increase the usage rate and comfort of parks, squares, etc., promote the balanced utilization of public resources, and create a female-friendly atmosphere. In contrast, poor lighting may lead to situations where women avoid using these spaces.

Research findings indicate that from a female perspective, the degree of completion and improvement of community supporting facilities has a significant impact on subjective perception (Table 6). Safety-related supporting facilities ensure women's travel and safety, comfortable environments enhance a sense of ease, and various activity areas catering to different age groups promote family relationships and intergenerational interaction. All these factors lead women to give higher evaluations of the completeness of community supporting facilities, strengthening their sense of identification and subjective perception toward the community. The correlation between the degree of female-friendliness and residential satisfaction is not significant ($r=0.040$). At the same time, subjective perception shows a certain correlation with the built environment of facilities. A good built environment of facilities makes residents feel visually comfortable and pleasant, and use facilities conveniently and efficiently, thereby generating positive subjective perceptions. In addition, when the built

TABLE 5 Reliability and validity test results of latent variables

Latent variable	C.R.	AVE	Cronbach alpha
Transportation (T)	0.820	0.331	0.803
Living houses (L)	0.952	0.877	0.913
Leisure and fitness (C)	0.849	0.553	0.836
Female-Friendliness (WF)	0.680	0.588	0.812
Perception (P)	0.738	0.694	0.819
Satisfaction (S)	0.723	0.439	0.780

TABLE 6 Satisfaction evaluation of facilities

Variable	Observation variable	Mean	Standard deviation	Principal index mean
T	T1	3.38	0.832	3.43
	T2	3.32	0.842	
	T3	4.20	0.880	
L	L1	3.29	0.808	3.43
	L2	3.49	0.790	
	L3	3.90	0.889	
	L4	3.90	0.777	
	L5	3.64	0.779	
C	C1	3.37	0.826	3.50
	C2	3.33	0.888	
	C3	3.43	0.874	
	C4	3.49	0.832	
	C5	3.37	0.940	
S	S1	3.76	0.972	3.76
	S2	3.83	0.754	
	S3	3.68	0.883	
WF	WF1	3.27	0.839	3.34
	WF2	3.19	0.998	
	WF3	3.41	0.847	
	WF4	3.87	1.079	

environment of facilities meets the actual living needs of residents and meets or exceeds their functional expectations, residents will give higher evaluations (33). Finally, a safe and comfortable environment will also enhance residents' living comfort and their identification and affection for the living environment, which is reflected in higher subjective perception evaluations.

In the demonstration of the indirect effect, it was found that the direct influence quantity of the "Environment → Perception → Satisfaction" path was 0.444, the indirect influence quantity was $0.941 \times 0.444 = 0.419$, and the total influence was 0.862 ($p < 0.001$). The direct impact of the "Environment → Satisfaction" path was 0.591 ($p < 0.002$). Studies have shown that the built environment has a significant indirect impact on residential satisfaction through subjective perception ($\beta = 0.418$, 95% CI [0.321, 0.532]). This indicates that 41.8% of the total impact of the built environment on satisfaction is mediated by the subjective perception of residents.

TABLE 8. Coefficient estimates for SEM.

Path information	Estimate	SE	C.R.	P
Environment → Transportation	0.204	0.096	1.888	—
Environment → Leisure and entertainment	0.958	0.138	6.938	***
Environment → Life business	−0.175	0.072	−2.428	**
Perception → Environment	0.942	0.043	24.334	***
Female-friendly → Environment	1.000	—	—	—
Satisfaction → Perception	0.444	0.124	3.586	***
Satisfaction → Environment	0.291	0.108	1.773	**
Satisfaction → Female-friendly	−0.048	0.163	−0.304	0.803
T11 → Transportation	1.000	—	—	—
T14 → Transportation	0.845	0.017	28.477	***
T15 → Transportation	0.820	0.016	21.867	***
L11 → Life business	1.000	—	—	—
L12 → Life business	0.854	0.005	27.487	***
L13 → Life business	0.864	0.006	27.711	***
L14 → Life business	0.767	0.002	26.323	***
L15 → Life business	0.872	0.008	23.235	***
C11 → Leisure and entertainment	1.000	—	—	—
C12 → Leisure and entertainment	0.742	0.020	34.224	***
C13 → Leisure and entertainment	0.748	0.043	22.268	***
C14 → Leisure and entertainment	0.558	0.032	17.338	***
C15 → Leisure and entertainment	0.628	0.017	28.138	***
F11 → Perception	1.000	—	—	—
F12 → Perception	0.885	0.033	22.845	***
F13 → Perception	0.837	0.034	24.284	***
W11 → Female-friendly	1.000	—	—	—
W12 → Female-friendly	0.538	0.042	16.404	***
W13 → Female-friendly	0.747	0.040	18.321	***
W14 → Female-friendly	0.778	0.044	24.878	***
S1 → Satisfaction	1.000	—	—	—
S2 → Satisfaction	0.278	0.023	10.821	***
S3 → Satisfaction	0.415	0.024	20.820	***

*p < 0.05, **p < 0.01, ***p < 0.001. The path “—” represents the latent (unmeasured) latent variable represented by the corresponding explicit variable.

Interestingly, the research found that recreational and entertainment facilities are more attractive to women than transportation and commercial living facilities. Recreational and entertainment facilities can provide women with richer emotional experiences and opportunities for self-actualization. Gyms, dance studios, and other places not only allow women to exercise and maintain their figure but also serve as platforms for them to pursue self-improvement and challenge their limits. In this process, women can feel the enhancement of their own strength and the expansion of their abilities, and gain a sense of achievement and confidence. Museums, theaters, and other cultural and entertainment venues can meet women's spiritual needs, allowing them to immerse themselves in different emotional worlds and pursue various emotions such as romance, fantasy, and emotion. In contrast, transportation facilities mainly meet basic travel needs and have a single function, making it

difficult to bring rich emotional experiences and social value to women; commercial living facilities, although they can meet shopping and consumption needs, are not as significant as recreational and entertainment facilities in terms of emotional satisfaction and social interaction.

With residence time (RES) as the factor and satisfaction (S1-4) as the dependent variable, the team adopted the single factor ANOVA test method to effectively analyze the influence of a single factor on the dependent variable. The correlation between family life satisfaction and residence time was statistically significant, and the *p*-value was 0.005 (Table 7). As shown in Table 8, pairwise comparison of the data of different groups is carried out to accurately identify the groups with significant differences. The results showed that female residents who lived for more than 10 years had the highest degree of satisfaction with family life compared with those who lived for 0–4 years and

5–9 years. In order to further refine the research results and clarify the differences in family life satisfaction of female residents in different residence periods, the research team conducted multiple comparative post-hoc tests (LSD). The results reveal a positive relationship between the increase of residence time and female residents' satisfaction with family life, that is, with the extension of residence time, female residents' satisfaction with family life shows an increasing trend.

4.4 Characteristics of female polymer site

As shown in Table 4 and Figure 5, the study found that women always gathered in the shopping malls around the community (25.1%), followed by the nearby parks (18.6%) and cafes/book bars/bars/Internet celebrities punching points (18.5%), while the fitness facilities in the community (9.4%) were the areas where women

gathered least. Further analysis shows that the reason why shopping malls have become women's favorite gathering place may be because they can meet a variety of consumer needs, from daily shopping to fashion and beauty, from catering and entertainment to parent-child activities, providing women with a one-stop leisure experience place. The high concentration of nearby parks reflects women's love for the natural environment and outdoor activities. Walking in the park and appreciating nature can both relax the body and mind and help maintain health and vitality (44). The appeal of cafe/book bars/bars/online celebrity check-in points may be due to their unique atmosphere and social attributes, which provide women with a warm space to meet friends, exchange emotions and share their lives, while also satisfying their pursuit of fashion, culture and novel experiences.

In contrast, the low aggregation rate of fitness facilities in the community suggests some potential problems. On the one hand, it may be that the types of fitness facilities are relatively simple and outdated, which cannot meet the diversified fitness needs of women, such as the lack of special equipment suitable for women such as yoga and pilates, or the limited space of the venue and overcrowding during peak hours, which affect the use experience of women (45). On the other hand, the lack of publicity and promotion may also be one of the reasons, many women may not know the specific functions and opening hours of the fitness facilities in the community, resulting in these facilities are not fully used. In order to improve the utilization rate of fitness facilities in the community, community managers can consider increasing the diversity and interest of facilities, regularly maintaining and updating equipment, holding some fitness activities or courses, attracting more women to participate in fitness activities in the community, promoting intergenerational communication and interaction, and creating a more healthy, harmonious and dynamic community atmosphere.

TABLE 7 Comparison between residence time and satisfaction

Observed variable	SES	Sum of squares	Mean square	F	p
S1	Interclass	0.506	0.054	0.264	0.754
	Intraclass	476.529	0.046		
S2	Interclass	1.152	0.076	1.052	0.304
	Intraclass	523.143	0.046		
S3	Interclass	5.236	1.042	2.250	0.035
	Intraclass	492.414	0.070		
S4	Interclass	5.051	2.210	5.366	0.009
	Intraclass	424.938	0.046		

TABLE 8 Single-factor ANOVA post-hoc test

Variable	Length of residence (I)	Length of residence (J)	Mean difference (I-J)	S.E.	P
S4	5–9	5–9	0.000	0.000	0.454
		10 above	-0.126*	0.033	0.036
	10 above	5–9	-0.000	0.000	0.444
		10 above	-0.127*	0.036	0.032
	10 above	9–14	0.126*	0.033	0.036
		5–9	0.127*	0.036	0.032

*The significance level of the mean difference was 0.05.

TABLE 9 Results of female gathering points

Aggregation type/frequency	Never	Seldom	Sometimes	Frequently
A1: Children's activity place in the community	24.6%	32.6%	31.2%	11.6%
A2: Leisure activities in the community	37.2%	31.6%	26.2%	5.0%
A3: Fitness facilities in the community	16.7%	38.3%	32.4%	9.4%
A4: Shopping malls around the community	12.7%	22.5%	29.3%	35.5%
A5: The neighborhood is surrounded by parks	33.5%	28.3%	16.6%	21.6%
A6: Neighborhood cafe/book bar/bar/Internet celebrity punching point	25.6%	32.0%	33.7%	18.5%
A7: Neighborhood beauty/nature/scenic/historical	18.4%	34.6%	34.0%	13.0%
A8: Neighborhood fitness/leisure space	26.1%	31.7%	31.3%	10.9%

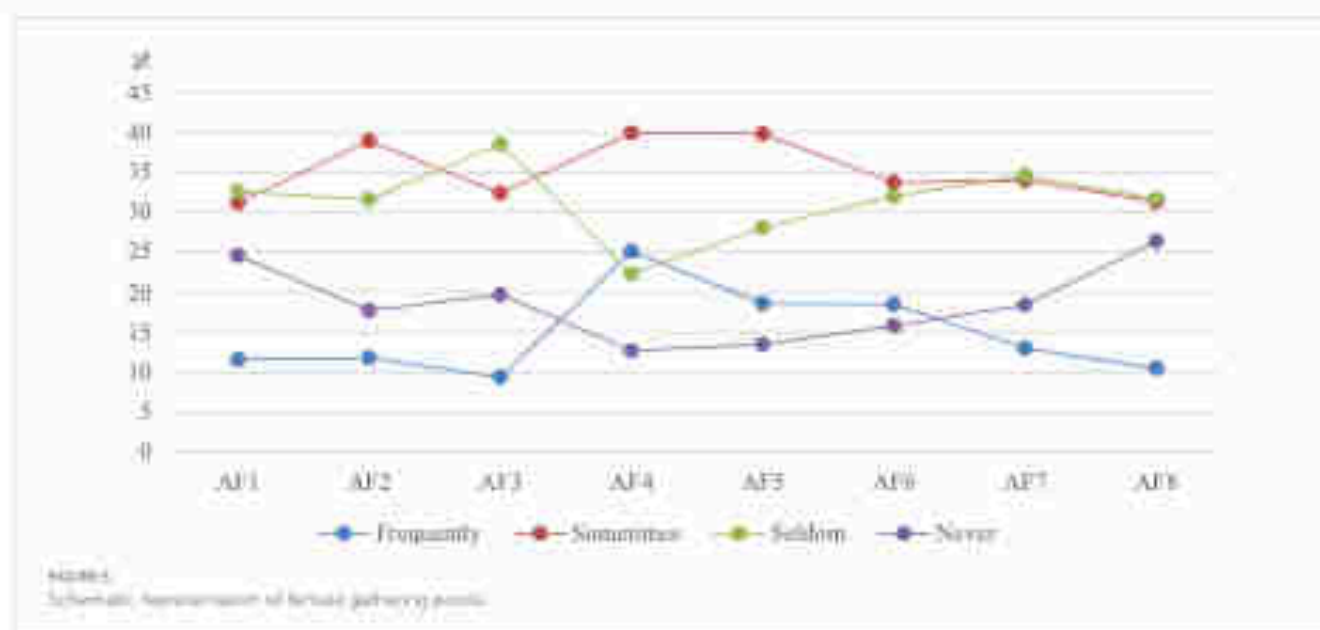


TABLE 10 Presents the results of the model.

Hypothetical path	Estimate	Testing
H1: Satisfaction \leftrightarrow Female-friendliness	-0.04	Not support
H2: Female-friendliness \leftrightarrow Environment	1.02	Support
H3: Perception \leftrightarrow Environment	0.34	Support
H4: Satisfaction \leftrightarrow Environment	0.54	Support
H5: Satisfaction \leftrightarrow Perception	0.44	Support

5 Discussion

This study takes 36 communities in Yangpu District, Shanghai as the research objects and explores the relationship between the built environment of residential supporting facilities and the friendliness of women, subjective perception, and residential satisfaction from the perspective of women. The research results not only enrich the empirical research on “female-friendly cities” in the Chinese context, but also provide a new perspective on the micro-mechanisms by which community facilities shape women’s life experiences.

5.1 Mechanism of facility environment and female experience

The core finding of this study is that the built environment of community facilities significantly affects female-friendliness and residential satisfaction, which is consistent with and expands on existing theories of social infrastructure. Urban social infrastructure (such as parks and commercial spaces) is crucial for promoting social interaction and a sense of belonging (24, 55). The research further clarifies this relationship by focusing on the female group, revealing that facilities are not merely functional spaces but carriers of gender needs: well-designed recreational facilities, safe lighting, and child-friendly areas directly enhance women’s sense of being cared for, thereby strengthening their sense of identity with the community.

It is worth noting that recreational and entertainment facilities are more attractive to women than transportation or commercial facilities. This finding is consistent with the qualitative study by Peng et al. (11), which emphasizes that women’s activity preferences are closely related to emotional experiences and social interactions. Gyms, community activity centers and parks not only meet physical needs, but also provide platforms for self-development and interpersonal connections. In contrast, transportation facilities mainly meet basic travel needs, while commercial facilities focus on utilitarian consumption and have a relatively small impact on shaping women’s emotional attachment to the community.

Another notable result is that there is no significant direct correlation between female-friendliness and residential satisfaction. Resident satisfaction is a multi-dimensional structure, influenced by basic living conditions and background factors (12). For women, although facilities that are friendly to women (such as mother-and-baby rooms and night lighting) are important, they may be secondary to core needs such as affordable housing or convenient commuting. Furthermore, the heterogeneity of female needs reflects that young single women prioritize safety and married mothers focus on childcare facilities (44), which may dilute the unified impact of female-friendliness on overall satisfaction.

5.2 Guiding women-friendly community construction

The research results have a clear impact on urban planners and decision-makers who aim to improve the quality of life for women. The first is to give priority to optimizing leisure and entertainment facilities. Given the strong appeal of the community to women, it should expand diverse recreational spaces such as yoga studios, book bars and parent-child activity areas, and ensure that these spaces are convenient, safe and well-maintained. This is in line with the initiative to build “women-friendly cities” and can be incorporated into local policies through incentives (8). Second, give full play to the intermediary role of subjective perception. Research has confirmed

that the built environment indirectly affects residents' satisfaction through their perception. Therefore, improving the "soft environment" is as important as upgrading the hardware. For instance, organizing women's cultural salons or volunteer activities can enhance their sense of belonging, even in communities with limited facilities and resources. Third, build female-friendly facilities in a targeted manner. As women's needs vary by age, family structure and lifestyle, a one-size-fits-all strategy is ineffective. For instance, communities with more young mothers should give priority to mother and baby rooms and children's playgrounds, while those with older women may need fitness trails and social lounges. Surveys that regularly assess the heterogeneity of demand will guide precise facility upgrades.

5.3 Limitations and future research

At the same time, there are some shortcomings in this study. First, due to the limitations of data acquisition approaches and methods, the selection of communities and indicators in Yangpu District of Shanghai is limited, and the current infrastructure situation in the residential area cannot be fully explained. Second, Yangpu District is selected as the research site in this paper, and the research scope can be expanded to include Pudong, Huangpu, Changning and other districts and counties in the future, so that the samples will be more comprehensive and objective. Third, this paper mainly uses cross-sectional data, which cannot well reveal the longitudinal mechanism of the impact of the built environment and subjective perception evolution of facilities within the scope of daily activities on the overall site satisfaction.

6 Conclusion

6.1 Hypothesis testing

As shown in Table 2, this paper carefully formulated five hypotheses around the issues related to concentrated housing, and based on the wild field investigation and detailed questionnaire data of 38 residential communities in Yangpu District, carried out in-depth analysis, and finally reached a clear and revelatory conclusion. After rigorous analysis, four hypotheses were established with strong data support, and another hypothesis was falsified. Specifically, there is no direct correlation between female friendliness in the community and residential satisfaction, and the path coefficient between the two is -0.04 , which cannot directly constitute the correlation hypothesis, so hypothesis 1 is falsified (Table 10).

There is a strong correlation between the quality of the built environment of the facility and the friendliness of women. Women can feel the community's care for women by using the facilities in daily life. When there are sufficient and reasonably arranged lighting facilities around the community, women will feel more secure when traveling at night, reflecting the community's attention to women's safety needs (40). The details of public restrooms also reflect the friendliness of women (10). A sufficient number of women's toilets and clean, well-equipped sanitation facilities can avoid embarrassing queues for women in public places, reflecting respect for and care for women's physiological needs. The presence of the mother and baby room provides great convenience for

nursing mothers, such as comfortable nursing environment and complete maternal and baby supplies, so that mothers can calmly take care of their children when they go out and feel the support and care of the community for nursing women (32), thus enhancing their sense of belonging and identity to the community. Therefore, hypothesis 2 is valid.

The quality of the built environment of the facility greatly affects the subjective perception and experience. High-quality facility environment can bring pleasure, comfort and convenience to women and improve their cognition of the quality of life. On the contrary, poor facility environment will cause negative emotions and reduce women's subjective perception of living environment, especially in commercial areas, so hypothesis 3 is valid. At the same time, the built environment and subjective perception of facilities have a certain impact on women's residence satisfaction. Humanized facilities environment, for example, the community is equipped with well-maintained fitness facilities, safe and comfortable children's play area, bright and clean public space, etc., can improve the convenience and comfort of women's daily life, so that they feel the quality of life and community care in the actual use of the process, and then enhance the recognition of the living environment. In terms of subjective perception, women's perception of community atmosphere, harmony of neighborhood relationship and community safety also affect their living satisfaction to a large extent (19, 32). A community full of friendly atmosphere, neighbors helping each other and good security will make women have a strong sense of belonging and security in psychology. Even if the facilities are not perfect, they can make up for some deficiencies by positive subjective feelings, which is different in the new and old residential communities. On the contrary, if there are defects in the construction of facilities, coupled with adverse subjective perception factors, such as apathetic interpersonal relations in the community, serious noise pollution, etc., it will greatly reduce women's satisfaction with living, and may even lead to their idea of moving out, so hypothesis 4 and hypothesis 5 are valid. Therefore, in the process of improving women's living satisfaction, it is necessary to pay attention to the optimization of the built environment of facilities and the creation of positive subjective perception, which complement each other and jointly create an ideal living space for women.

6.2 Suggestions for management and builders

According to the experimental data and conclusions obtained in this paper, the following suggestions can be provided for the managers and policy makers of Shanghai urban construction. First of all, in terms of planning and policy formulation, in view of the low perception of female residents on the female-friendly degree of residential areas in Yangpu District, policy documents are issued to encourage and guide the construction of female-friendly supporting facilities in residential areas, such as giving tax incentives and plot ratio incentives to developers or properties that add female-only facilities. Set up a special fund to subsidize the renovation of women-friendly facilities in old residential areas to increase the enthusiasm of builders and managers. At the same time, the evaluation index system of supporting facilities in female-friendly residential areas should be established, and the facilities construction in each residential area

should be quantitatively evaluated on a regular basis, and the evaluation results should be published to the public.

Secondly, in terms of optimizing the rationality of facility layout, the layout of supporting facilities in residential areas should be rationally planned, and the principles of convenience, accessibility and safety should be followed. Business service facilities, medical and health facilities, educational facilities, etc. are centrally arranged in the center of the residential area or near the main entrances and exits to form a convenient life service circle and reduce the travel distance and time cost of female residents. Placing women-only facilities in a visible, easy-to-find, relatively separate and private location while ensuring a safe and comfortable surrounding environment. Pay attention to the connectivity between different supporting facilities, through the walking path, bicycle path and other green transportation means to organically connect the facilities, so as to facilitate the conversion and passage of female residents between different facilities.

Finally, in terms of the establishment of facility operation and management mechanism, based on the characteristics reflected in the female cluster site, a sound operation and management system and service norms for supporting facilities in the residential area can be formulated, and the operation subjects, management responsibilities, service content and charging standards of the facilities can be clarified. For commercial service facilities, we should strengthen investment management, introduce businesses that meet women's consumption needs and quality requirements, and provide diverse and high-quality goods and services for female residents. For public service facilities, such as community activity centers, libraries, gyms, etc., the opening hours should be reasonably arranged, the utilization rate of the facilities should be improved, and professional management and service personnel should be equipped to ensure the normal operation and service quality of the facilities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics Review Committee of the College of Publishing, University of Shanghai for Science and Technology. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

References

1. Dillingham, M. The bad and the female: gender differences in wellbeing and negative consequences of economic inequality. *Thompson Econ Policy J Public Policy* (2011) 80 (25–32). doi: 10.1006/jtp.2011.01001
2. Mosemola, K. Urban planning and quality of life: a review of pathways linking the built environment to subjective well-being. *Cities* (2011) 31(5), 932–940. doi: 10.1016/j.cities.2011.10.029
3. Whitman, C., Andrién, C., and Stylianidis, K. Pathways for women's safety in the city: 'You hope for a good table'. *Environ Urban* (2014) 26, 443–56. doi: 10.1177/0958242914337580

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ZF: Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. JY: Conceptualization, Investigation, Software, Visualization, Writing – original draft. JS: Investigation, Software, Supervision, Validation, Visualization, Writing – original draft.

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Conflict of interest

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4. Yang, C. The urban rights of cities: inequalities and women's autonomous experiences in South Korea's smart home city. *Int J Urban Innov* (2021) 10 (1), 44–69. doi: 10.1177/1042253921101742

5. Campes, T., Georgiadis, G., and Barban, A. Developing cities for citizens: supporting gender equity for successful and sustainable urban mobility. In O. Gervais, S. Murgain, S. Shari, A. Roshchuk and C. Gama, editors. *Computational ICIS'22 and its applications*, ICCIS 2022 workshop, PT 1, vol. 13342. Cham, Switzerland: Springer International Publishing AG (2022). 416–22.

8. Li, Q., Hsu, H., Zhang, X., Chen, J., Li, W., and Lin, Y. Evaluation of public space in Beijing's old residential communities from a female citizen's perspective. *Sustainability* (2023) 15:4007. doi: 10.3390/su15104007
9. Cai, Q., Cui, Y., Yang, C., Zhang, S., Huang, Y., Jiao, Y., et al. Women-oriented exploration of perceived safety of walking routes between home and mass transit: a case study and methodology test in Guangzhou. *Buildings* (2023) 13:713. doi: 10.3390/buildings13060713
10. Gong, W., Huang, S., White, M., and Langenhove, D. Walkability perceptions and gender differences in urban fringe new town: a case study of Shanghai, LAND (2023) 12:1359. doi: 10.3390/land12071359
11. Mounif, R.A., Benmouh, T., and Elmaliki, M. Greenbelt shaping (time for all) gender's angle in the city planning framework, Hong Kong. *Cities* (2024) 150:105011. doi: 10.1016/j.cities.2024.105011
12. Peng, B., Ng, J.Y.Y., and Ho, A.H. Barriers and facilitators to physical activity for young adult women: a systematic review and Delphi synthesis of qualitative literature. *Int. J. Behav. Nutr. Phys. Act.* (2023) 20:21. doi: 10.1186/s12942-023-01421-7
13. Power, S. The COVID-19 pandemic has increased the care burden of women and families. *Seminars in Perinatology* (2020) 44:47–55. doi: 10.1016/j.semper.2019.12.004
14. Guo, K., Deng, Y., Huang, L., Wang, D., Cao, X., Wang, L., et al. Sustainability-oriented urban renewal and low impact development applications in China: case study of Yangpu District, Shanghai. *J. Sustain. Water Res. Environ.* (2018) 4:40017908. doi: 10.1007/s10241-018-0004-7
15. Gelfand, J., Chinn, J., and de Almeida, R. Measuring spatial inequality of urban park accessibility and utilization: a case study of public housing development in Auckland, New Zealand. *Environ. Urban. Plan.* (2018) 24:7100173. doi: 10.1016/j.enurbanplan.2018.07.005
16. Li, X., and Lin, H. The influence of subjective and objective characteristics of urban human settlements on residents' life satisfaction in China. *LAND* (2023) 12:1400. doi: 10.3390/land12121400
17. Nieuwen, D., Guo, W., Kinski, S., and Tölgner, H. Structural evaluation on neighborhood facilities in relation with residential satisfaction and preference. *Am. J. Environ. Res.* (2014) 12:164–69. doi: 10.5841/ajer.2016.108.01
18. Wells, W.M., and Yang, T. Neighborhood design and walking: a quasi-experimental longitudinal study. *Am. J. Prev. Med.* (2006) 34:313–9. doi: 10.1016/j.amepre.2004.07.019
19. Zeng, L., Deng, Y., Yan, L., and Lin, A. Perceived safety in the neighborhood: exploring the role of built environment, social factors, physical activity and multiple purposes of influence. *Buildings* (2023) 13:2. doi: 10.3390/buildings13020002
20. Gargallo, I., Garcia, X., Benegas-Alier, M., Martinez, J., Piferrer, E., and Vell-Casas, T. Women's safety perception assessment in an urban stream corridor: developing a safety map based on qualitative GIS. *Landsc. Urban Plan.* (2024) 198:104779. doi: 10.1016/j.landurbplan.2022.104779
21. Patraik, H. Gender and participation in community-based adaptation evidence from the dismantled climate crisis protest in Bengal. *World Dev.* (2021) 142:105446. doi: 10.1016/j.worlddev.2021.105446
22. Sharkey, A., and Lin, H.M. Gender bias in the built environment: how young women experience in public space in undivided and divided in London. *Urban. Des.* (2023) 28:331–34. doi: 10.1080/1357480X.2022.2123370
23. Vardoulakis, S., Phillips, S., and McAdam, M. Online communities and environmental justice: practices of building, being and belonging. *Geogr. Res.* (2022) 34:742–61. doi: 10.1080/00141801.2022.204360
24. Chen, T., Ren, X., Xu, X., Wang, R., and Xu, T. Evaluation of living environment quality in urban residential area under the concept of urban renewal: a case study of Binjiang District, Hangzhou, China. *Sustainability* (2023) 15:14104. doi: 10.3390/su151014104
25. Hsu, L., and Jia, H. Spatial heterogeneity of public service facilities in the living circle and its influence on housing prices: a case study of central urban Hubei, China. *LAND* (2022) 11:1095. doi: 10.3390/land11071095
26. Latham, A., and Lyons, J. Social infrastructure and the public life of cities: studying urban vitality and public space. *Geogr. Compass* (2019) 13:e12444. doi: 10.1111/gco.12444
27. Lin, H.-H., Chang, K.-H., Tseng, C.-H., Lee, T.-S., and Cheng, C.-H. Can the development of religious and cultural tourism build a sustainable and friendly life and leisure environment for the elderly and promote physical and mental health? *Int. J. Environ. Res. Public Health* (2021) 18:11999. doi: 10.3390/ijerph181211999
28. Pei, L., Zheng, X., Li, L., and Yu, Z. RAC: partial area planning for re-adjusting the layout of traffic routes to city's public transport. *IEEE Trans. Intell. Transp. Syst.* (2023) 24:1231–40. doi: 10.1109/ITITS.2022.3176929
29. Song, Y., Wang, Y., and Zhou, M. Public space satisfaction evaluation of new city fringe communities in urban fringe area: a study of Suzhou, China. *Int. J. Environ. Res. Public Health* (2023) 20:793. doi: 10.3390/ijerph20070793
30. Wang, W., Zhou, Y., Chen, J., Cheng, W., and Chen, J. Analysis of location selection of public service facilities based on urban land accessibility. *Int. J. Environ. Res. Public Health* (2021) 18:516. doi: 10.3390/ijerph18050516
31. Wang, Z., Hu, X., and Hoshino, T. Assessing the equity and evidence of urban visual perceptual quality with time when street view imagery. *Cities* (2024) 143:104704. doi: 10.1016/j.cities.2023.104704
32. Nichols, L., Boudier, N., and Vireo, T. Disadvantaged communities have lower access to urban infrastructure. *Environ. Plan. B Urban Anal. City Des.* (2023) 50:331–49. doi: 10.1177/2399808323113104
33. van Woe, R. Accessibility and equity: a conceptual framework and research agenda. *J. Transport Geogr.* (2022) 104:103421. doi: 10.1016/j.jtrangeo.2021.103421
34. Peng, X., Peng, Z., Tong, T., Zhang, G., and Wang, W. Assessing comfort in urban public spaces: a structural equation model involving environmental attitude and perception. *Int. J. Environ. Res. Public Health* (2023) 20:1287. doi: 10.3390/ijerph20041287
35. Wolf, B.J., Harrington, K.M., Clark, D.L., and Miller, W.W. Sample size requirements for structural equation models: an evaluation of Power, Bias, and solution propriety. *Adv. Psychol. Assess.* (2013) 22:293–34. doi: 10.1177/0145445512449927
36. Carsten, A., McKee, L., and Schlegel, M.D. Social relationships and group dynamics inside a community recreation facility for women. *Int. J. Environ. Res. Public Health* (2018) 15:1019–25. doi: 10.3390/ijerph15061019
37. Cai, J., Shao, X., Yang, J., Yin, L., and Huang, X. Promoting neighborhood attributes to enhance neighborhood satisfaction: an impact asymmetry analysis. *Cities* (2018) 79:101854. doi: 10.1016/j.cities.2018.101854
38. Cai, J., and Wu, X. Exploring the importance of transportation infrastructure and accessibility in connection with urban and suburban neighborhoods: an application of gradient boosting decision trees. *Transport. Planning. Sci.* (2019) 10:128667209
39. Huang, Z., and Du, X. Assessment and determinants of residential satisfaction with public housing in Guangzhou, China. *Habitat Int.* (2015) 47:214–24. doi: 10.1016/j.habitat.2015.01.001
40. Wang, Z., and Magalhães-Chaparro, H. Gender mainstreaming in the urban space to promote inclusive cities. *J. Sustainable Res. Southern Africa* (2022) 35:1161. doi: 10.4001/35-1161-1362
41. Zhang, Y., Cao, Y., Zhao, C., Lin, J., and Li, X. Subjective well-being of professional females: a case study of Dalian high-tech industrial zone. *Front. Psychol.* (2022) 13:804294. doi: 10.3389/fpsyg.2022.804294
42. Anderson, J.C., and Gerbing, D.W. Structural equation modeling in practice: a review and recommended two-step approach. *Psychol. Bull.* (1988) 103:411–21. doi: 10.1037/0033-2909.103.3.411
43. Hu, B., and Medsker-Gomez, A. The effect of estimation methods on SEM fit indices. *Asia. Pac. J. Adv. Stat.* (2020) 30:425–45. doi: 10.1177/0924646019869162
44. Cai, K., and Guo, H. The problem with having too similar constructs of 10 when BMM2S and CFI diverge. *Statist. Papers* (2018) 57:229–38. doi: 10.1007/s00737-017-0413-1
45. Jack, S.C., Jones, L., and Hsu, H. Gendered alpha: a comparison in scoring reliability and validity in professional health assessment. *ES. Energy Environ.* (2023) 23:1077. doi: 10.3390/ee23051077
46. Swedler, L.J., Beckstead, J.C., and Johnson, M. Factor analysis is a tool for survey analysis: using professional role orientation inventory as an example. *Phys. Ther.* (2000) 80:704–99. Annual Conference and Exposition of the American Physical Therapy Association. doi: 10.1093/ptp/80.4.704
47. Wang, Q.-C., Liu, X., Ren, T., Zhang, F.-J., He, Y.-T., Su, K.W.M., et al. Community resilience in city emergency: exploring the roles of environmental perception, social justice and community attachment in subjective well-being of vulnerable residents. *Environ. Res.* (2023) 217:114638. doi: 10.1016/j.envres.2022.114638
48. Rink, C.T., Larsen, J.B., Colledge, S., Charney, L., and Prokeš, C.T. Gender differences in connection to nature, aesthetic preferences, and nature-based recreation among college students in Brazil and the United States. *Environ. Sci.* (2019) 45:115–37. doi: 10.1080/01676369.2020.1803310
49. O'Brien, M.E., Loden, A.M., Chen, L.L., Brown, H., Hahn, H.A., Somers, M.E., et al. Mechanisms, barriers and associated problems among female microentrepreneurs: a novel assessment strategy. *PLoS One* (2022) 17:e0241138. doi: 10.1371/journal.pone.0241138
50. McDowell, H., Leckie, C., King, A., and Zahraoui, Rami, S. Female-owned Indian bakeries: how their satisfaction is derived differently from males. *Ent. Space Manage.* (2018) 38:136–74. doi: 10.1016/j.esm.2017.03.007
51. Pyatitskaya, A., and Bonneau, K. One single data public transport contribute to inclusive night mobility? Exploring Gila's night bus network from a gender perspective. *Transp. Policy* (2020) 87:41–50. doi: 10.1016/j.transp.2020.01.002
52. Bastago-Garcia, T., Hernandez, M.H., Sanchez, A., Rueda-Hu, L.L., Su, A., Renteria-Garcia, T., et al. Family friendly urban tradeable in Barrios Pasa: a mixed-methods study using photo-ethnography. *J. Glob. Health* (2022) 12:040577. doi: 10.7195/jgh.2022.040577
53. Jönsson, V., Burns, E., and Redman, A. Place of sanctuary: an appreciative inquiry approach to discovering how community support breastfeeding and parenting. *Am. J. Breastfeed.* (2019) 14:23. doi: 10.1186/s13006-019-0218-9
54. Lin, X., and Clark, W. Using the social influence of electronic word-of-mouth for predicting product sales: the moderating effect of review or reviewer helpfulness and product type. *Sustainability* (2020) 12:2952. doi: 10.3390/su12122952
55. Zhang, T., Wu, C., and He, L. Experiencing authenticity in microentrepreneurial responsible behavior: assessing the effect of personal value, moral emotion, and motivation on voluntary heritage tourism. *Front. Psychol.* (2022) 13:891464. doi: 10.3389/fpsyg.2022.1041464



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A BEACON through the walls: AI-assisted tacit knowledge extraction from built environments

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Introduction: The rapid urbanization of contemporary society has created environments that often overlook the human needs of their inhabitants. This paper presents BEACON (Built Environment Architecture Cognitive Ontology Network), a comprehensive multi-layer ontological framework to support reasoning about the gaps between practical urban design and the requirements that emerge from social, cognitive and neuroarchitectural findings concerning urban living.

Methods: BEACON integrates seven analytical layers: physical, experiential, social, normative, behavioral, cognitive, and neural; a systematic network with descriptions ranging from physical design elements to individual neural responses.

Results: Integrating these layers addresses critical limitations in current neuroarchitecture research by providing: (1) a formal ontological structure for organizing complex environmental-neural relationships; (2) a practical methodology for extracting tacit knowledge from built environments, applying it to an analysis of Pachino's central square in Sicily, comparing historical (1910) and contemporary (2025) configurations to reveal how architectural modifications cascade through all analytical dimensions; and (3) an example design of an immersive XR platform for both research and applied urban planning, enabling real-time, multi-sensory analysis of urban environments.

Discussion: This transdisciplinary integration envisions a paradigm shift from post hoc environmental analysis to proactive design optimization.

KEYWORDS

neuroarchitecture, neurosymbolic AI, ontology design, urban cognition, extended reality, built environment, neural response

1 Introduction

Neuroarchitecture makes us understand and design urban environments by applying neuroscientific principles to investigate how built environments impact human neural dynamics, perception, and overall experience (Jeffrey, 2019). Its extension into "neurourbanism" encompasses the design of healthier, more sustainable urban environments informed by objective neuroscientific findings beyond formal design principles (Kazak and Yurcek, 2022).

As urbanization accelerates globally, with projections indicating that over 68% of the world's population will reside in cities by 2050 (United Nations, 2018), the imperative for

scientifically informed, human-centered design approaches becomes increasingly critical. This shift recognizes that rapid urbanization has frequently overlooked the psychological and neurological needs of city dwellers, resulting in various physical and mental challenges for urban residents (Kuyuk and Yucet, 2012).

Research in neuroarchitecture has established clear relationships between environmental features and neural responses across multiple domains. In the domain of spatial cognition and navigation, human wayfinding exploits an evolved brain system dedicated to processing navigable space, which also supports episodic memory formation (Jeffery, 2019). Key neural components include place cells that fire in context-dependent manners, head direction cells providing directional information, and grid cells involved in distance-measuring processes sensitive to environmental boundaries.

Poorly designed layouts, particularly those with rotational symmetry, can increase disorientation and cognitive burden, especially for older adults who struggle with landmark-based disambiguation (Jeffery, 2019).

Deshmukh et al. (2022) introduced the neural basis for behavioral modulation in built environments, pointing to the neural structures and processes involved. Their reconstruction is used as a neural basis for our ontology framework (Section 5).

Karachirou and Turner (2017) advanced this understanding through portable Electroencephalography (EEG) studies, demonstrating that different architectural features elicit distinct patterns of brain activity related to attentional engagement and cognitive load during wayfinding. Their research revealed that specific visual cues in urban environments can either facilitate or impede cognitive mapping and orientation, with the brain's response being dynamic and influenced by the sequential experience of moving through environments rather than static perception alone.

The visual characteristics of urban environments profoundly influence human emotional states through measurable neural mechanisms. Strickmann et al. (2022) identified fractal geometry as particularly significant, demonstrating that environments incorporating multiple fractals with optimal dimensions—D values between 1.5 and 1.5, common in natural scenes—reduce stress and mental fatigue while inducing positive aesthetic experiences. This "fractal fluency" appears to be evolutionarily hardwired, with the human visual system efficiently processing natural fractal patterns through "effortless looking" that reduces physiological stress.

Complementing this research, Benatti et al. (2017) established through EEG studies that curvilinear spaces generate significantly higher pleasure and arousal ratings compared to rectilinear forms, correlating with increased activity in the anterior cingulate cortex (ACC). Remarkably, this ACC activation occurs within 30 milliseconds of stimulus onset, indicating rapid, unconscious processing of architectural forms that influences emotional states before conscious awareness.

The concept of Attention Restoration Theory, originally proposed by Kaplan (1995), is supported in contemporary neuroarchitecture research. Mally et al. (2014) and Anwar et al. (2022) conducted systematic literature reviews demonstrating that complex urban built environments offer fewer capacities for cognitive recovery and restoration, leading to directed attention fatigue (when you spend extended periods engaged in tasks

that require concentrated mental effort, depleting the brain's capacity for focused, voluntary attention). Built environments consistently activate brain regions associated with higher-order visual processing, episodic memory, spatial navigation, and stress responses, including the amygdala and areas related to directed attention fatigue (Ainslie, 2010). Conversely, natural environments promote attentional restoration by engaging simpler, bottom-up attentional processes that require fewer mental resources. These environments activate brain areas associated with basic visual processing, visuospatial perception, sensory integration, and emotional control, including the anterior cingulate cortex and prefrontal, supporting restorative experiences.

1.1 Limitations and Research Gaps

Despite these advances, current neuroarchitecture research faces significant limitations (Rad et al., 2023) that hinder its practical application.

First, neuroscientific data are not easy to associate with urban situations (Marquardt et al., 2024). Selected studies offer insights into the neuroarchitectural linkwork, but simulations of design choices with their neuroscientific counterparts are not available off-the-shelf.

Second, neuroarchitecture suffers from a lack of integrated frameworks (Wang et al., 2022). Current research tends to focus on specific aspects of urban experience rather than comprehensive frameworks simultaneously addressing multiple scales and dimensions. Most studies examine individual features or limited sets of variables, while we need to simulate complex interactions between physical, social, and cognitive factors in urban environments (Mahmoud, 2024). The field seems to lack a "systematic framework" (Mahdavi et al., 2023; Salinasova, 2024) for modelling the complex relationships between environmental features and human responses.

Third, many studies rely on laboratory settings or simplified virtual environments that may not capture the complexity of real urban experiences (Lee et al., 2022). While Mobile Brain/Body Imaging (MBI) studies (Deloux et al., 2021) enable measurement during real-world navigation (Ruhn and Gellhaus, 2024), the volume and breadth of data required to train robust, generalizable models remain limited.

1.2 Our Contribution

We introduce REACON (Built Environment Architecture Cognitive Ontology Network), a multi-layer formal ontology framework to analyze urban environments across seven integrated layers, from physical elements to neural responses. We represent it by using the OWL Description Logic (World Wide Web Consortium, 2012), enabling computational reasoning about complex environmental relations. We apply the Polanyi method (De Gennaro et al., 2025) for automatically extracting tacit (a.k.a. implicit) knowledge (Polanyi, 1966) from built environments, integrating multimodal data acquisition and representation (Tupayachi et al., 2014) with ontology-augmented knowledge graph generation (Gargano and Nardisac, 2023). Furthermore, we present an extended reality

model designed to enable real-time, immersive multi-sensory environmental analysis (Hassanodifa, 2024).

We demonstrate REACON through a detailed analysis of Pachino's central square in Sicily, revealing how architectural design functions as a social engineering device that shapes neuro-cognitive development and community dynamics across historical periods. This approach moves beyond descriptive research toward design tools that can actively improve urban environments for human wellbeing.

2 Theoretical foundations

The complexity of urban environments demands a systematic methodology for extracting the tacit knowledge (Polanyi, 1966) embedded within their design. The architecture and formal representations that we contribute integrates multiple analytical perspectives, assuming that much of the knowledge associable with built environments operates below conscious awareness—inhabitants may not articulate why certain spaces feel comfortable or oppressive, yet these feelings arise from discoverable relationships between environmental features and human responses. Three foundational research paradigms have been singled out, which accommodate our need for transdisciplinary links between architecture (Pattern Language), cognitive neuroscience (Predictive Coding), and computational methods (Ontology Design Patterns). Finally, we have taken advantage of the soft analytic flexibility provided by Generative AI to implement simulations of a system based on the three foundations. The implementation enables a customized conditioning for ontology-augmented knowledge graph generation for multilayer analysis of built environments.

2.1 Christopher Alexander's pattern language as a theoretical bridge

Christopher Alexander's seminal work on pattern languages (Alexander, 1977; Alexander, 1979; Alexander, 2000) provides a theoretical foundation that bridges traditional architectural intuition and contemporary neuroarchitecture research. Alexander introduced the novel concept that successful built environments emerge from interconnected best practices ("patterns") operating across multiple scales, from regional planning down to architectural details.

Alexander's insight aligns with current neuroscientific findings about measurable human responses to environmental features. For example, spaces that feel "alive," "whole," or "comfortable" can now be understood through objective measures of stress reduction, attention restoration, and positive neural activation patterns documented in contemporary neuroarchitecture research (Jeffery, 2006; Friedman et al., 2021).

Alexander identified 253 patterns, ranging from large-scale "Distribution of Towns" to specific details like "Window Place." Each pattern describes a design problem and its solution in terms of spatial relationships, human activities, and environmental qualities. They operate through "morphogenetic sequences," where smaller patterns combine to generate larger coherent structures

that support human flourishing.¹ This hierarchical organization parallels REACON, where physical design elements cascade through experiential, social, and behavioral layers to influence cognitive and neural responses. Alexander's emphasis on pattern interconnectedness provides theoretical support for understanding how modifications at one scale create ripple effects throughout the entire environmental system.

Contemporary neuroarchitecture research provides empirical validation for many of Alexander's intuitive observations. His patterns emphasizing natural light and human-scaled proportions correspond directly to documented neurocognitive benefits of biophilic design and fractal geometry (Friedmann et al., 2021). Alexander's advocacy for spaces with "positive outdoor space" and "gardens at multiple levels" aligns with research demonstrating stress reduction and attention restoration through exposure to natural elements (Chen et al., 2016). Similarly, Alexander's patterns addressing spatial configuration such as "Sequence of Sitting Spaces" and "Intimacy Gradient" reflect principles now understood through research on spatial cognition and social behavior in built environments (Kamathkrisna and Turner, 2017).

Alexander's methodology contributes several key concepts relevant to multi-layer environmental analysis. His emphasis on "diagnosis before design" parallels the systematic assessment approaches required for understanding complex environmental systems across multiple analytical dimensions. The pattern language focus on "forces" acting within design situations provides a framework for understanding how different layers of environmental influence interact and sometimes conflict. This perspective supports understanding how modifications at one analytical layer create effects that propagate through other layers, ultimately influencing overall human experience in ways that cannot be predicted from examining individual components in isolation. Alexander principles are being used to ground automated evaluation of built environments (Gullingorn, 2023).

2.2 Neuroscientific foundations

REACON builds upon established neuroscientific principles demonstrating how environmental features influence brain functions, in particular about neural processing of space, experiential embodiment, predictive coding, fractal proportions, natural elements, and urban density. The brain processes environmental information through parallel pathways operating at different scales—from basic visual processing in occipital regions to complex social-spatial integration in temporoparietal networks (Messeri et al., 2023).

Environmental experience is fundamentally embodied, with spatial navigation, social positioning, and cognitive processing intimately connected through shared neural substrates. Eichen and Gallant (2024) synthesized research demonstrating that architectural features directly influence neural activity patterns—high ceilings activate brain regions involved in visuospatial exploration, open rooms are universally preferred

¹ See <https://www.patternlanguage.com/en/127200> for a more variety of interconnected sequences.

over enclosed ones, and large symmetrical spaces positively affect users' emotional states. Even subtle elements like window shapes significantly influence cortical activity, with pleasant shapes showing larger effects in the left hemisphere. This embodied perspective underscores that our physical movement through space fundamentally shapes our cognitive and emotional responses.

The brain continuously generates predictions about environmental features based on prior experience, with architectural regulations shaping these predictive models over time. This predictive processing process (Friston, 2010) helps explain why certain design patterns feel intuitively "right" or "wrong"—they either align with or violate our learned expectations about how spaces should function. Regular exposure to specific spatial configurations strengthens neural pathways associated with those patterns, creating deeply ingrained responses that operate largely below conscious awareness.

Specific architectural features consistently influence neurocognitive responses in measurable ways. Classical architectural proportions, recognized as statistical fractals, demonstrate positive effects on visual perception, attention, and emotional responses (Brislmann et al., 2022).

The integration of natural elements, including sunlight, water, vegetation, and natural geometries—collectively termed biophilic design—activates brain areas associated with basic visual processing, visuospatial perception, sensorial integration, and emotional control (Brislmann et al., 2022). The presence of natural elements appears to engage different neural processing pathways than built features, promoting restoration through bottom-up attentional processes that require fewer cognitive resources.

Urban density represents another critical factor linking environmental design to neural responses. Research has established clear connections between urban density and neural stress responses, with overcrowding acting as a social stressor that activates amygdala regions related to fear and negative affect (Ancora et al., 2022). Urban upbringing and current city living are associated with altered neural social stress processing and increased risk for mood and anxiety disorders. Environmental diversity emerges as a critical factor for positive affect and individual wellbeing, suggesting that monotonous urban environments may contribute to psychological distress through understimulation of neural reward systems.

2.3 Ontology design and multi-agent simulation

REACON employs formal ontology design patterns (Holler et al., 2016) to structure the complex relationships between environmental features and human responses (see Section 3). This formalization serves multiple purposes: enabling computational reasoning about environmental-human relationships, providing a consistent vocabulary for interdisciplinary communication, and facilitating the integration of diverse data types within a unified analytical structure.

Following pattern-based design (Wangye et al., 2016), an established agile method for designing and evaluating computational ontologies using competency questions (what an expert would ask an ideal knowledge-based agent or AI to assist in regular or creative work), and *reasonable best practices* known

generalised solutions to model a schema that would create the possibility to answer those questions), we started by acquiring requirements from the analysis of neuroarchitecture literature, and the needs emerged therein to link multistructured knowledge.

Since we are acting in exploratory/creative mode, and in absence of previous established practices or elicitation methods, we decided to condition multiple state-of-the-art Large Language Models (LLMs) (Norval et al., 2023) with an agentic approach (Acharya et al., 2023) that we call "Mixture of Experts Simulation" (MES). Each simulated agent represents the expertise in one of the background knowledge areas to discuss and collectively map inter-area relationships. The simulation involved expertise in Urban Design History, Architectural Phenomenology, Social Geography, Sociology, Behavioral Psychology, Cognitive Neuroscience, and Systems Integration, each contributing domain-specific insights while collaborating to understand systemic interactions.

Through structured discussions, MES artificial experts produced insight requirements for each area, and about inter-area relationships. The Urban Design Historian emphasized how physical structures embody temporal layers of social intention. The Architectural Phenomenologist explained how spatial volumes create experiential hierarchies transcending mere physical measurement. The Social Geographer demonstrated how spatial experience directly translates to social positioning through proximity regulation. The Sociologist revealed how spatial-social arrangements become codified into self-reinforcing normative expectations. The Behavioral Psychologist showed how spatial arrangements compel behavior through multiple mechanisms including affordances and observational learning. The Cognitive Neuroscientist explained how habitual behaviors create measurable neural changes through preferential synaptic strengthening. The Systems Integration Specialist synthesized these insights into integrated requirements, revealing how each layer both constrains and enables adjacent layers.

This collaborative agentic approach proved essential for understanding how modifications in any knowledge area create cascading effects throughout the system, making it emerge the bridging requirements, and identifying critical junctures where small changes produce impacts. The resulting requirements are explained in the next Section 3.

3 Multi-layer requirements

The architecture emerging from MES includes seven knowledge layers that ultimately connect physical environmental features to neural responses. The architecture is meant to address the limitations of traditional environmental psychology approaches, which often focus on isolated variables without considering their complex interactions. The architecture has been used as requirements to design the ontology applied in the conditioning of LLMs for environmental tacit knowledge extraction.

3.1 Layer architecture

Seven layers represent distinct but interconnected levels of analysis, each capturing specific aspects of the environment-human

relationship while contributing to an integrated understanding of spatial experience.

Layer 1: Physical Environment constitutes the foundational level, encompassing tangible architectural and urban design elements. This layer includes structural elements such as buildings, boundaries, and materials; spatial relationships including proximities, heights, and sightlines; and environmental conditions such as light, sound, and movement pathways. These measurable, objective features of the built environment can be documented through traditional architectural methods and enhanced through contemporary techniques such as photogrammetric reconstruction and material analysis. The physical layer provides the substrate upon which all other experiential layers are built, yet its influence extends far beyond mere constraint—the specific configuration of physical elements actively shapes possibilities for experience and behavior.

Layer 2: Experiential Environment captures the translation of physical features into possibilities for action and sensory experience. This layer encompasses spatial affordances and constraints, sensory experiences including visual hierarchies and acoustic qualities, and movement possibilities and limitations. It bridges objective physical properties with subjective human experience, operationalizing Gibson's concept of "affordances"—the action possibilities offered by the environment (Gibson, 1979). For instance, the height differential between civic buildings and common structures does not merely represent a physical measurement but creates experiential hierarchies of prominence and dominance that profoundly influence how people navigate and understand the urban space.

Layer 3: Social Dynamics addresses how spatial configurations enable and constrain social interactions. This layer includes access regulations both explicit and implicit, visibility and surveillance dynamics, as well as opportunities and limitations for status display. Built environments contain social activities but also actively shape them through visibility patterns that determine who can see whom, proximity regulations that govern social distances, and territorial demarcations that establish group boundaries. As spatial experiences directly translate to social positioning, a plaza becomes not simply a void between buildings but a carefully calibrated arena where social proximity and distance are regulated through architectural means.

Layer 4: Normative Regulation captures the implicit and explicit rules governing behavior in different spatial contexts. This layer encompasses behavioral expectations that vary by location, ritual and ceremonial scripts embedded in spatial design, and the boundaries and consequences of transgression. These norms emerge from the interaction of cultural values with spatial affordances, creating location-specific behavioral codes that become self-reinforcing through visibility and social endorsement. When spatial-social arrangements become codified into normative expectations, the physical environment functions as a silent educator, continuously instructing inhabitants about appropriate conduct.

Layer 5: Behavioral Manifestation documents the observable behaviors emerging from the interaction of spatial affordances, social dynamics, and normative expectations. This layer includes habitual movement patterns that develop through repeated navigation, frequencies and qualities of social interaction shaped by spatial configuration, and the performance of social roles in spatially

appropriate ways. It represents the actualization of behavioral possibilities within environmental constraints, where spatial arrangements compel behavior through multiple mechanisms including affordances that make certain actions easier, constraints that make others difficult, and observational learning facilitated by visibility patterns.

Layer 6: Cognitive Processing addresses the mental processes engaged by environmental features. This layer encompasses how spaces direct attention through visual hierarchies and focal points, facilitate memory formation and association through distinctive features and regular patterns, and reinforce mechanisms of personal and social identity through repeated exposure to status-conferring spatial arrangements. The cognitive layer represents the interface between environmental stimuli and conscious experience, where automatic processing of spatial information shapes thoughts, memories, and self-concept.

Layer 7: Neural Activation is the brain activity that underlies all other layers—it's the biological foundation for how we experience and respond to our environment. This includes three key brain processes: spatial navigation (involving brain cells that help us understand location and movement), social awareness (particularly in brain regions that process social situations), and emotional responses (pathways that connect environmental features to our feelings). When we repeatedly experience certain places or situations, our brains literally rewire themselves through neuroplasticity, strengthening the neural connections associated with those experiences. These brain changes often happen without our conscious awareness, creating automatic responses to environmental cues that can last a lifetime.

3.2 Inter-layer relationships

The explanatory power of these requirements adds value from understanding their interconnections. Each layer both constrains and enables adjacent layers through specific bridging mechanisms that create cascading effects throughout the system.

The relationship between Physical and Experiential layers demonstrates how material properties and spatial configurations create affordances and sensory experiences. Architectural elements such as ceiling height, room geometry, and material textures do not merely exist as neutral features but actively create perceptions of volume, boundaries, and relationships. A narrow doorway does not simply restrict physical passage but creates an experiential transition that heightens awareness of moving between spaces (Hudrunsky and Copeland, 2006). The acoustic properties of hard surfaces versus soft furnishings shape the auditory environment, influencing whether a space feels intimate or exposed (Baron, 1995).

The Experiential to Social transition reveals how sensory experiences and movement possibilities shape patterns of social encounter. Spatial configurations that create natural gathering points through comfortable microclimate conditions or attractive views facilitate certain types of social interaction while discouraging others. The regulation of social proximity through architectural means—such as the width of pathways determining whether people must acknowledge each other when passing—demonstrates how experiential features translate directly into social dynamics (Tidell, 1990).

The crystallization of Social patterns into Normative expectations represents a crucial transition where repeated behaviors become codified rules. When certain spatial arrangements consistently produce specific social configurations—such as hierarchical seating in religious buildings—these patterns transform into expectations about appropriate behavior. The visibility of norm compliance or violation, facilitated by spatial design, creates self-reinforcing systems where social pressure maintains behavioral standards without explicit enforcement.

The Normative to Behavioral relationship encompasses how internalized rules guide actual behavioral choices. This influence operates through multiple channels: affordances that make norm-compliant behavior easier, constraints that make violations more difficult, and the observational learning that occurs when behavioral models are visible to others. The spatial environment thus functions as a behavioral script, continuously cueing appropriate actions through its configuration.

The progression from Behavioral patterns to Cognitive schemas represents the internalization of spatial experience into mental models. Habitual movement patterns shape cognitive maps not merely of physical space but of social space—understanding where one belongs and how to navigate social hierarchies embedded in spatial form. Regular behaviors in specific locations strengthen associations between places and activities, creating cognitive schemas that automatically activate when entering similar spaces.

The final transition from Cognitive processing to Neural activation represents the biological encoding of environmental experience. Repeated cognitive patterns, such as processing social hierarchies in spatial terms when navigating status-marked environments, create preferential neural pathway strengthening. The convergence of spatial and social information in brain regions such as the temporoparietal junction illustrates how architectural experience becomes neurologically embedded, creating structural brain changes through neuroplasticity that persist long after leaving the environment.

These relationships operate bidirectionally, creating feedback loops that allow higher-level processes to influence lower-level configurations. Social movements advocating for accessible design, for instance, resonate in cognitive recognition of exclusion (Layer 6), manifest through collective behavior (Layer 5), challenge existing norms (Layer 4), alter social dynamics (Layer 3), demand new experiential possibilities (Layer 2), and ultimately result in physical modifications such as ramp installations (Layer 1).

These system-driven requirements should also account for temporal dynamics, since environmental influences operate across multiple timescales. Immediate responses, such as the rapid activation of the Anterior Cingulate Cortex (ACC) when encountering collisional versus rectilinear forms (Roues et al., 2017), occur within milliseconds. Medium-term adaptations, such as the development of cognitive maps and behavioral routines, unfold over days to months. Long-term impacts, including the neural architectural changes associated with chronic environmental exposure, may develop over years or decades. Our nomological structure must therefore incorporate temporal operators that can represent these varied timescales and their interactions.

4 Case study: pachino's central square

An application of the analytic requirements in Section 3 to Pachino's central square in Sicily intends to demonstrate how architectural design functions as social engineering, shaping not merely behavior but neural development itself. The analysis is performed across two time periods—1910 and 2023—revealing how design modifications continue to influence human experience across all analytical dimensions.

4.1 Historical context

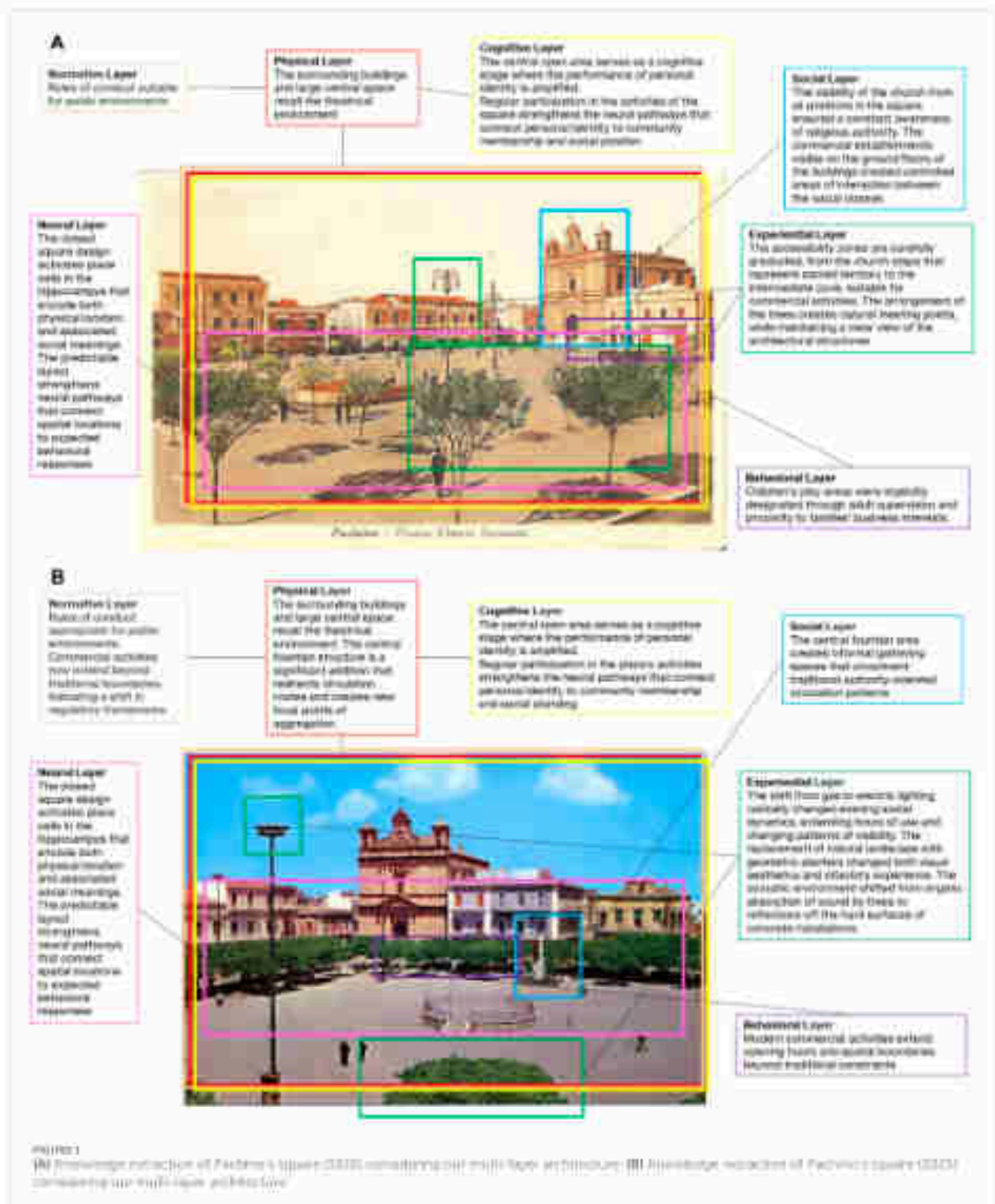
Pachino's central square, established in the 18th century, exemplifies the deliberate encoding of social hierarchy through architectural means. The square's carefully orchestrated layout—positioning the Town Hall, Chiesa Madre (Mother Church), aristocratic homes, and commercial establishments around a central void—created what we might now recognize as a sophisticated apparatus for social control and identity formation. This was not merely a gathering space but a three-dimensional diagram of power relations made manifest in stone and space.

The square operated as what Foucault (1979) might have termed a "disciplinary mechanism," though predating his analysis by centuries. The design created a spatial panopticon where visibility ensured behavioral compliance without constant active surveillance. Citizens moving through the square necessarily performed their social roles under the watchful presence of institutional architecture. The centralization of civic, religious, and economic power around a single space ensured that daily life continuously reinforced existing hierarchies. Regular gatherings for market days, religious festivals, and civic ceremonies transformed abstract social relations into embodied experiences, with each person's position in the square reflecting and reinforcing their position in society.

4.2 Multi-layer analysis

A detailed analysis across the seven requirement layers shows a complex system where physical design elements cascade through multiple processing layers to shape individual and collective experience. The comparison between 1910 and 2023 configurations demonstrates both continuity and change in these multilayered influences (Figure 1).

Layer 1: Physical Environment Analysis (what are the fundamental tangible architectural and urban design elements?). In the historical configuration of 1910, the Chiesa Madre's positioning as the dominant architectural anchor was no accident—its elevated position and ornate facade created an unavoidable focal point from any position within the square. The municipal investment in ornate street lighting, visible in period photographs, indicates recognition of the square's role as civic theater. The rectangular perimeter of three-story buildings created an enclosed environment that focused attention inward while establishing clear boundaries between public and private space. Contemporary modifications include the replacement of organic landscaping with standardized concrete planters, altering the square's microclimate and sensory qualities. Modern lighting systems extend usable hours but change



the quality of evening illumination from the warm, variable glow of gas lamps to uniform electric brightness.

Layer 2: Experiential Environment Analysis (how physical features translate into possibilities for action and sensory experience?). The historical configuration's carefully graduated

zones of accessibility created what Alexander might term an "intimacy gradient"—from the sacred threshold of the church steps through the commercial middle ground to the informal edges. Natural tree placement created comfortable microclimates while maintaining visual connections to authority structures,

balancing comfort with surveillance. The elevation changes between different areas established natural viewing hierarchies that reinforced social stratification through embodied experience. Contemporary modifications have fundamentally altered these experiential qualities. The transition from gas to electric lighting extends activity hours but eliminates the temporal rhythms created by the labor of lamp-lighters and the gradual dimming of fuel-based illumination. Geometric planters provide less shade and seasonal variation than trees, reducing sensory richness while increasing visual uniformity. The acoustic environment has shifted from organic sound absorption to hard surface reflections, creating a more reverberant space that may increase stress through noise exposure.

Layer 3: Social Dynamics Analysis (how spatial configurations enable and constrain social interactions?). Historical photographs from 1910 demonstrate clear spatial segregation patterns, with formal dress indicating elite presence near institutional buildings while working-class figures occupy peripheral positions. This was not merely customary but architecturally subordinated—the design created natural territories that would feel inappropriate to transgress. The visibility of the church from all positions ensured constant awareness of religious authority, creating what we might term “architectural conscience.” Ground-floor commercial establishments provided controlled interaction zones where different classes could engage in necessary economic exchanges within defined spatial and behavioral parameters. Contemporary patterns show significant democratization, though subtle hierarchies persist. Economic barriers replace some spatial ones—outdoor café seating creates new forms of territorial exclusion based on consumption rather than birthright. Tourist presence introduces unprecedented diversity in behavioral norms and spatial usage patterns. The central fountain area enables informal gatherings that bypass traditional circulation patterns focused on institutional buildings, creating new possibilities for social formation outside established hierarchies.

Layer 4: Normative Regulation Analysis (what rules govern behavior in different spatial contexts?). Historical religious processions followed routes that physically enacted theological hierarchies—the path from Chiesa Madre through the square created a sacred geography that participants bodily experienced. Market activities were spatially confined with implicit rules about appropriate commercial behavior varying by location within the square. Dress codes and deportment expectations created invisible boundaries more powerful than physical barriers. The positioning of civic buildings enabled surveillance while church bells provided temporal regulation, structuring daily rhythms through acoustic signals that penetrated private space. Contemporary norms show relaxation of formal restrictions while maintaining underlying respect patterns. Tourism introduces negotiation between local expectations and visitor behaviors, creating dynamic normative landscapes. Commercial activities now extend beyond traditional boundaries both spatially and temporally, indicating fundamental shifts in the regulation of economic life.

Layer 5: Behavioral Manifestation Analysis (how spatial affordances translate into observable behaviors?). Historical promenading patterns followed prescribed routes that displayed social status while respecting institutional boundaries—a “*perseggiata*” was not random wandering but choreographed social display. Religious observances created predictable gathering and

dispersal patterns tied to liturgical schedules, with the square’s design facilitating efficient crowd flows during major festivals. Commercial interactions followed temporal rhythms aligned with agricultural cycles and religious calendars. Spatial analysis describes how people maintained appropriate distances from authority structures while maximizing visibility within acceptable zones. Contemporary behaviors show increased informality though persistent structural influences. Tourist photography introduces new spatial practices—the search for optimal viewpoints creates novel circulation patterns. Extended commercial hours and relaxed spatial boundaries reflect changed economic structures. Yet respect for religious space boundaries persists, suggesting deeply internalized spatial norms resistant to surface modernization.

Layer 6: Cognitive Processing Analysis (how the square shapes mental processes across time periods?). The Chiesa Madre’s architectural prominence creates automatic attentional capture, priming religious consciousness regardless of conscious intention. The symmetrical building arrangement guides visual scanning in patterns that continuously return attention to institutional structures (Varbo, 1967). The central void functions as a cognitive stage where personal identity performance becomes heightened through visibility. Landmark buildings serve as spatial anchors for episodic memory formation, with personal experiences becoming intertwined with institutional presence (Jansen and van Turenhout, 2004). Regular participation in square activities strengthens neural pathways connecting personal identity to community membership. The predictable spatial layout facilitates cognitive mapping while embedding social hierarchies within spatial memory structures.

Layer 7: Neural Activation Analysis (what are the biological substrates of spatial experience?). The enclosed square design activates hippocampal place cells that encode not merely physical location but associated social meanings—neural maps that integrate “where” with “who belongs where” (Torelli et al., 2010). The predictable layout strengthens neural pathways connecting spatial positions to behavioral repertoires through repeated activation patterns. Proximity to authority structures triggers amygdala activation related to social vigilance, creating embodied respect through mild stress responses (Aldridge, 2010). Mirror neuron systems activate through observation of others’ spatial behaviors (Rizzolatti and Sinigaglia, 2004), facilitating rapid social learning of appropriate conduct. Positive experiences during community celebrations create dopaminergic reinforcement, associating the space with social reward and belonging (Shum and Maurice, 2014). The integration of spatial and social processing in regions like the temporoparietal junction illustrates how architectural experience becomes neurologically embedded (Jase and Kattwiler, 2005). Regular exposure from childhood literally shapes neural architecture, creating lifelong predispositions that persist even as conscious beliefs may change.

The Pachano analysis demonstrates how architectural design creates environments where abstract social concepts become lived neural realities. The square functions as a machine to influence people—citizens whose neural pathways have been shaped by repeated exposure to spatial hierarchies. The comparison between historical and contemporary configurations shows persistence and change. While surface behaviors may appear modernized, continuing influences of spatial structure on social dynamics and individual experience are still present. Physical modifications create

new possibilities while earlier patterns leave traces in collective memory and learned behaviors.

The social engineering impact of Pachino's spatial configurations lies not merely in its physical persistence but in its capacity to create self-reinforcing systems across multiple analytical layers. Even as contemporary modifications introduce new elements—electric lighting, concrete planters, tourist flows—the fundamental spatial grammar established centuries ago continues to organize experience. This is a principle for urban design: architectural interventions create cascading effects that persist far beyond their original context, embedding themselves in neural structures, social practices, and cultural memory in ways that resist simple modernization. The square thus serves as both historical artifact and living laboratory, revealing how built environments function as active agents in the continuous production of human consciousness and community life.

5 BEACON: a formal ontology network of environmental experience

We have translated the systematic requirements from Section 4 into BEACON (Built Environment Architecture Cognitive Ontology Network), a formal ontology network² that serves multiple functions. It enables computational reasoning about environmental-human relationships, provides a rigorous vocabulary for interdisciplinary communication, and establishes logical foundations for integrating different data types. We use the Web Ontology Language (OWL, W3C, 2009), ensuring compatibility with knowledge graph technologies and knowledge representation standards. The agile pattern-based methods described by Hinder et al. (2016) have been applied to design ontologies that follow domain and task requirements, as explained in the previous sections.

5.1 The ESBM ontology: a neurocognitive foundation

The Environment-Sensitumotor Behavior Modulation (ESBM) ontology provides the neurocognitive foundation for neuroarchitectural knowledge extraction. It formally models the low-level neurophysiological mechanisms that link an agent's perception of the environment to their automatic, sensitumotor-driven behaviors. It focuses on the "how" of human-environment interaction from a predictive processing (Friston, 2010) and enactive neuroscience perspective.

5.1.1 Core ontology patterns

The ESBM ontology is structured around a few core ontology patterns that represent agents with their neurocognitive architecture and the immediate stimuli they encounter (Figures 2–3).

1. **Agent as Substrate.** At the center is `dul:Agent`, imported from the DOLCE Ultra Lite foundational ontology (Prusini

and Gargano, 2016)³. The core axiom establishes that an agent is inextricably linked to its own neurocognition; every `esbm:NeuralStructure` (e.g., `esbm:Polyvixar`) is axiomatically defined as something that `dul:isPartOf` some `dul:Agent`, which `dul:isParticipatingIn` a `esbm:NeuralProcess` (e.g., `esbm:PredictiveProcess`), and a `esbm:NeuralStructure` `esbm:isSubstrateFor` a `esbm:NeuralProcess`.

2. **Stimulus-Response Pattern.** This pattern models the immediate interaction with the environment. An `esbm:EnvironmentalFeature` represents a distinct aspect of the environment that `esbm:elicits` an `esbm:SensitumotorResponse`, the core class representing a neuro-body reaction.
3. **Predictive Coding Pattern.** This pattern models the brain's predictive mechanisms. A `esbm:Prediction` is an `esbm:NeuralRepresentation` that is compared against an incoming `esbm:SensorySignal`. This comparison possibly `esbm:generates` a `esbm:PredictionError`, which in turn `esbm:updates` the original `esbm:Prediction`, completing the error-correction loop. Predictions are the neural grounding of conceptual forms, i.e., situation schemas that are used to anticipate and interpret environmental situations (`esbm:Prediction` `esbm:isShapedBy` a `frameset:Frame`).
4. **Thalamic Integration Pattern.** This pattern represents the role of thalamic nuclei in processing information. Since the ontology distinguishes neural structures from the processes they host, `esbm:Polyvixar` structures do not directly modulate activity, but `esbm:Polyvixar` `esbm:isSubstrateFor` a `esbm:NeuralProcess` which, in turn, `esbm:modulates` neural oscillations like `esbm:AlphaRhythm`. This structure-process distinction, combined with detailed property hierarchies (e.g., making `esbm:regulates` and `esbm:modulates` sub-properties of a general `esbm:influences` property), creates a more verifiable and precise model.

ESBM is a reusable foundational model of the low-level machinery that allows an agent to perceive and automatically react to their environment, grounding higher-level descriptions (`frames`) of the experience (`frame:accertion`) of environmental features in plausible neurophysiological processes.

5.2 The BEL ontology: modeling the multi-layered environmental experience

The Built Environment Layers (BEL) ontology represents how built environments shape human experience. It imports ESBM to ground built environmental experience analysis across seven distinct but interconnected layers. Where ESBM focuses on the low-level "how," BEL provides the structure for the higher-level "what" and "why."

5.2.1 Core patterns

BEL represents an experience as a hub that connects components from the analytical layers described in previous sections (Figure 6).

² <https://github.com/caldagel/pork/labels/ontology/bel/bel.owl>

³ <http://www.celtology.it/ontology/bel/bel.owl#owl:dul:BEL.owl>

1. The *bel-EnvironmentalExperience* Hubs: This is the core class of the BEL ontology. It is a subclass of *framester:FrameOccurrence*, conceptualizing an experience as a specific, active, contextualized instantiation of a conceptual frame. Axioms enforce that every *bel-EnvironmentalExperience* must have a *doI-Agent* as its *bel-hasExperiencer* and must involve components from all seven aspects: *bel-involvesPhysicalElement*, *bel-involvesAffordance*, *bel-involvesSocialPattern*, *bel-involvesNormativeRule*, *bel-involvesBehavioralPattern*, *bel-involvesCognitiveProcess*, and *bel-involvesNeuralResponse*.
2. The Causal Chain Pattern: The primary structural pattern in BEL is the causal flow of influence between the layer aspects, modeled with a chain of object properties. A *bel-PhysicalElement* *bel-enables* an *exm-Affordance* (the experiential aspect). This *exm-Affordance* then *bel-shapes* a *bel-SocialPattern*, which *bel-crystallizes* into a *bel-NormativeRule*. The *bel-NormativeRule* *bel-guides* a *bel-BehavioralPattern*, which *bel-influences* a *bel-CognitiveProcess*. Finally, the *bel-CognitiveProcess* *bel-activates* an *exm-SensoryMotorResponse* (the neural aspect). This flow is enforced through axioms, making the dependency chain explicit.
3. Temporal Dynamics and Measurement: The BEL ontology incorporates time and measurement to enable diachronic analysis and empirical grounding. Temporal classes like *bel-HistoricalConfiguration* and *bel-ExperientialMoment* allow for modeling across different timescales. Data properties such as *bel-hasFactualDimension* and *bel-hasAttentionDuration* provide hooks for associating quantitative data with conceptual entities, linking the formal model to measurable real-world phenomena.
4. Grounding in ESBM: The BEL ontology ensures its higher-level concepts are grounded in neuroscience by linking them directly to ESBM classes. For instance, *bel-CognitiveProcess* is a subclass of *exbm-NeuralProcess*, and the experiential and neural aspects are directly represented by *exbm-Affordance* and *exbm-SensoryMotorResponse*, respectively.

BEL's *bel-EnvironmentalExperience* with the causal flow between its constituent parts, provides a transdisciplinary theory to represent and reason about how built environments shape human and social life.

5.3 The SIM ontology: modeling the dynamics of active inference

The *Active Inference Simulation* (SIM) ontology provides the vocabulary and formal structure needed to simulate the dynamic, cyclical process of an agent's enacted cognition. While the BEL and ESBM ontologies describe the "what" (the layers of experience) and the underlying "how" (the neurocognitive machinery), the SIM ontology models the "when" and "why" of the agent's actions over time. It makes the steps of the active inference loop—perception, belief updating, prediction, and action—explicit and traceable.

5.3.1 Core patterns

The SIM ontology is designed with patterns that represent the *statal and probabilistic nature of agents' interaction with their environment* (Figure 7).

The State Chain Pattern: The simulation's timeline is modeled as a sequence of discrete *sim-SimulationState* individuals, linked by the *sim-precedesState* property. Each state represents a snapshot of the simulation, containing the agent's observations, beliefs, and the outcomes of its inferences at that moment (*sim-atTimeStep*).

The Multilayer Prediction Pattern: A crucial distinction is made between two levels of prediction. The high-level, conceptual *sim-Prediction* (e.g., predicting a social event) is formally linked to the underlying neurocognitive machinery that implements it via the *sim-mediatedBy* property, which points to an *exbm-PredictiveProcess*. This explicitly connects the cognitive stratum to the neural stratum.

The Probabilistic Belief Pattern: The agent's cognitive state is represented as a probabilistic landscape. A *sim-AgentBeliefState* *sim-hasBelief* in multiple *sim-Belief* individuals. Each *sim-Belief* is a qualified statement about a state of affairs (*sim-aboutState*) and is associated with a specific *sim-hasProbability*, representing the agent's confidence.

The Policy Selection Pattern: Active inference frames action as selecting the best *sim-Policy* from a set of possibilities. Each policy is annotated with its calculated *sim-withExpectedFreeEnergy* (EFE) and a resulting *sim-hasSelectionProbability*. The agent selects the policy that is most likely to minimize EFE, and this choice is recorded in the state chain via the *sim-hasSelectedPolicy* property.

By formalizing these dynamic and probabilistic patterns, the SIM ontology makes BEACON move from the static description of an environment to a dynamic simulation of an agent enacting its experience within that environment.

Figure 8 provides an interlayer diagram for the main classes and properties from the three ontology modules.

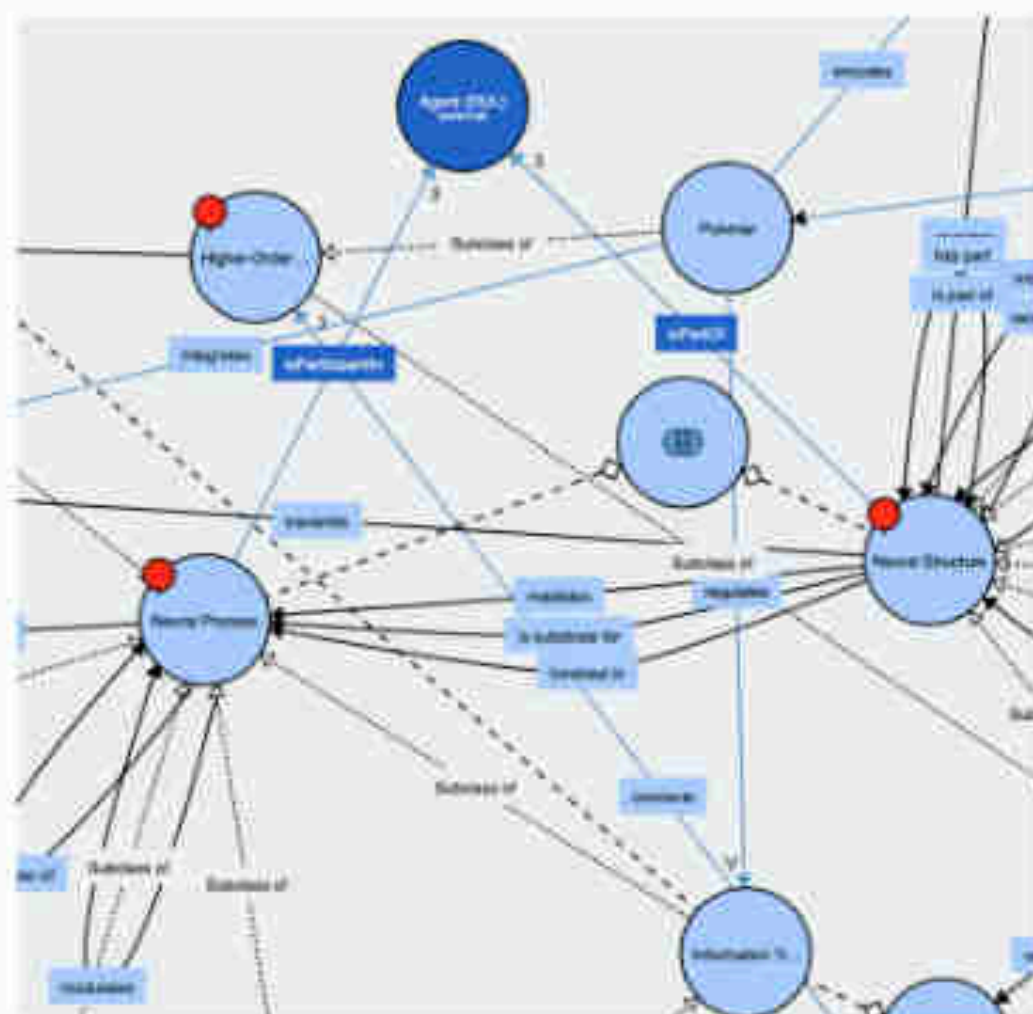
5.4 The pachino ontology: a case study

The Pachino ontology serves as a concrete instantiation and proof-of-concept for the ESBM and BEL modules of BEACON. It translates a qualitative description of a built environment—the main square of Pachino, Sicily—into a formal, machine-readable knowledge graph. Its purpose is to validate the theoretical models and to create a dataset that can be queried to generate insights and answer complex questions.

The ontology primarily consists of individuals (entities, relations, facts) that are instances of classes defined in BEL and ESBM. It models two main scenarios, each represented as a distinct individual of type *bel-EnvironmentalExperience*: *pachino:PachinoExperience_1910* and *pachino:PachinoExperience_2025*. Each experience is linked to a *doI-Agent* (e.g., *pachino:HistoricalCitizen_Generic*) and a temporal configuration (e.g., *pachino:PachinoTime_1910*).

Components from each layer are instantiated and linked to their respective experience. For example, for the 1910 experience:

1. Physical: The "dominant architectural anchor" is instantiated as *pachino:PL_ClaudioMadrèAnchorage_1910*.



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(*isBelPhysicalElement*) and linked to the experience via *hasInvolvedPhysicalElement*.

2. **Experiential:** This physical element belies the pachino EA, *GraduatedAccessibility*, 1910 affordance.
3. **Social:** This affordance, in turn, belies the pachino SD, *SpatialIntegration*, 1910 social pattern.
4. **Normative, Behavioral, Cognitive, and Neural:** The causal chain is instantiated layer by layer, connecting individuals like pachino NR, *SacredProcessionalRoutes*, 1910, pachino RP, *FormalPromenading*, 1910, pachino CP, *AttentionalCaptureChase*, 1910, and finally a specific neural impact like pachino NR, *AmygdalaActivation_Authority*, 1910 (an *enhancementofresponse*). Each is connected to the pachino *PachinoExperience*, 1910 and to the prior element in the chain, making the flow of influence explicit at the instance level.

The same process is repeated for the 2023 configuration, creating a parallel set of instances that allows for direct comparison. The Pichius knowledge graph exemplifies how to make the P5WM and

life testable, allowing researchers to formally trace a path from a design decision to its predicted neural impact.

5.5 A neurosymbolic simulation of an enacted environmental experience

The static descriptions provided by the ESRM and BEL ontologies, even when instantiated as a rich knowledge graph like `pachinowowl`, represent a snapshot in time. To provide an embodied foundation for task knowledge extraction, we also simulate the dynamics coupling between an agent and its environment, using the SIM ontology. The active inference component, which underpins the ESRM ontology, requires a predictive or generative engine (Part et al., 2024) to anticipate plausible futures and to guide behavior. While a full probabilistic implementation is not in the scope of this paper, we can effectively simulate a generative Bayesian engine using a Large Language Model (LLM) as a “neurosymbolic oracle” tasked with generating plausible knowledge graph updates that represent the agent’s predictions. The

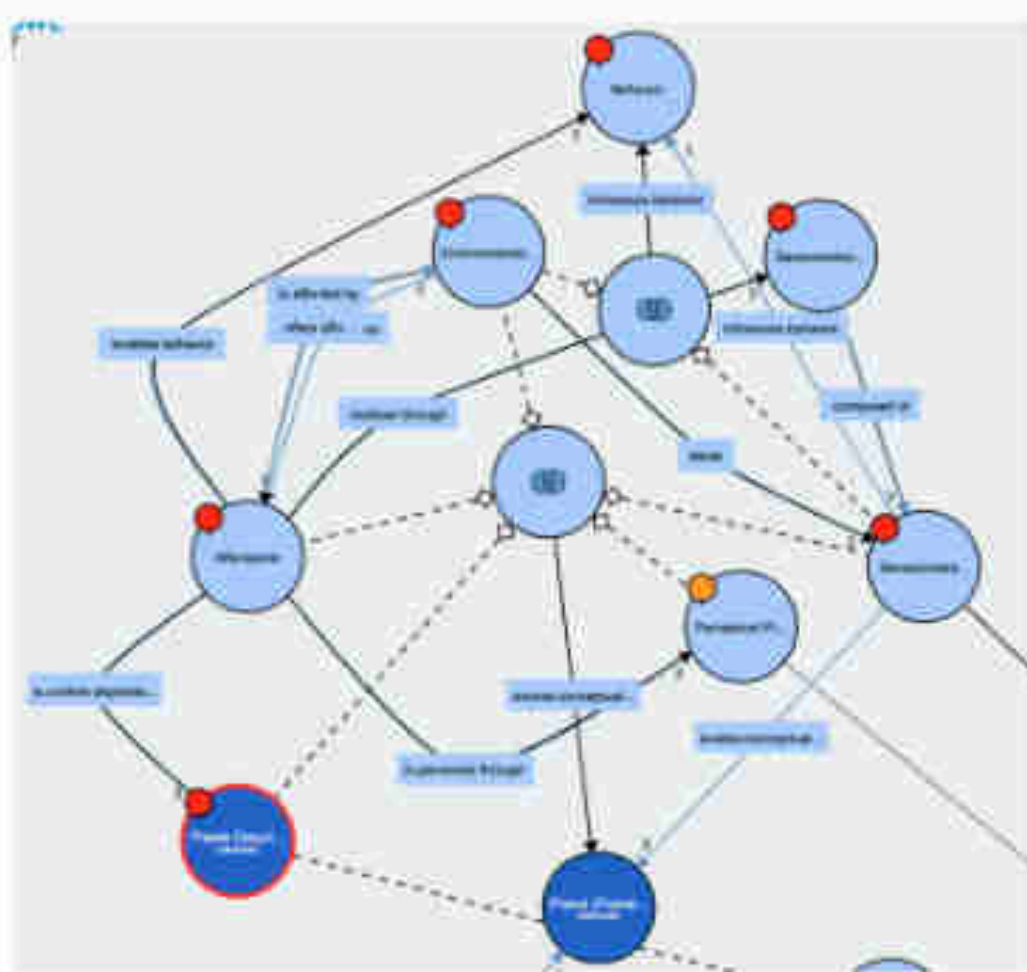


FIGURE 3
TABLE 3. Long-term effects of treatment with the experimental feed.

process unfolds as a cyclical loop, moving from the current state of the knowledge graph to an LLM-generated prediction, which then informs an action that updates the knowledge graph for the next cycle.

5.5.1 Simulation flow: a minimal case from Pachino (2025)

Let's consider a minimal case: a dul-Agent (e.g., a modern tourist) begins its bel-EnvironmentalExperience at the contemporary Puchino square (puchinoPuchinoExperience, 2025). We will represent the dynamic simulation as a series of states:

Section 4 = 11 Initial Perceptions and Prior Beliefs

- **Knowledge Graph Setup (KG, θ)** The simulation begins with an initial state. The knowledge graph contains the agent, their ongoing experience, and their first key observation.
 - `pachino:ModernTourist` `Generic` `rdf:type` `bal:Agent`
 - `pachino:Pachino` `Experience_2023` `bal:has` `Experience`
 - `pachino:ModernTourist` `Generic`

- pachino Pachino Experience_2023 betwines Physical Element pachino PE_Central Elevated Structure_2023
- The Generative Task (LLM Conditioning) We provide the initial KG sets to the generative engine (the LLM). The conditioning asks the LLM to act as the agent's internal generative model, based on the ESDM and REI ontologies.

"You are an agent situated in an environment described by the following knowledge (a realization of \mathcal{KG}): (i) You have (not perceived) the (action) \mathcal{P} ; (ii) Centrality and structure, 2015, based on the causal pattern in the \mathcal{ML} , ontology generate a "Predicted \mathcal{KG} " that represents the most plausible affordances and social patterns this observation induces."

Point 1 = 1: Production Generation (The LLM as Generative Engine)

- **Knowledge Graph State ($KG_{t_predicted}$):** The LLM, leveraging its understanding of context and the patterns embedded in our

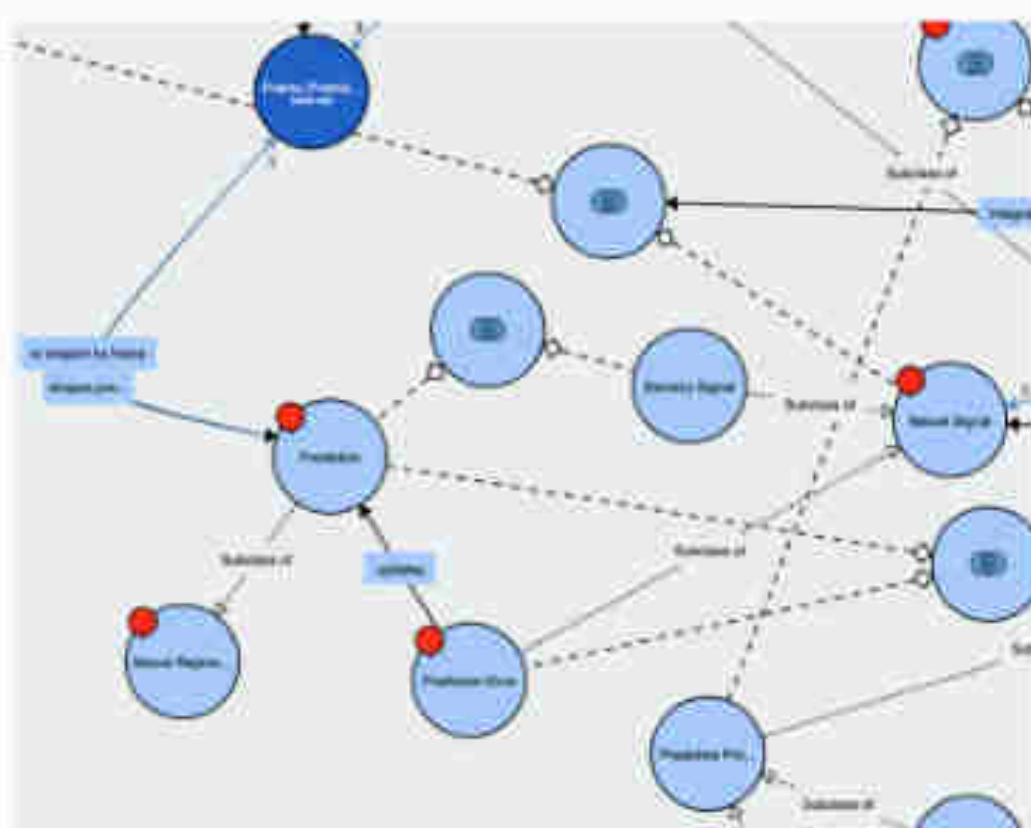


Figure 4
2009 The commission has been paid back at 100%, compared against 100% in 2008

ontology training, generates a new set of triples representing the agent's prediction. This is the simulation of the agent sampling (predicting) from their internal model of the world. The output is not a single value but a plausible future state of the EG.

- `pachecoFE_CentralJewelryStructure_2025` `bel` enables `pachecoEA_InformalGatheringAffordance_2025`.
 - `pachecoEA_InformalGatheringAffordance_2025` `bel` shapes `pachecoSF_InformalGatheringFountain_2023`.
- **Probabilistic Interpretation:** While the LLM outputs explicit probabilities, its choice to generate these specific individuals over others (e.g., predicting "informal gathering" instead of "formal promenade") represents a higher implicit probability for that future state, given the observation of a modern central fountain. This generated, ICG, predicted serves as the agent's expectation that needs to be fulfilled.

State 1 = 2: Action Selection and KG Update

- The Generative Task (LLM Prompt): The agent must now select an action (o-bits behavior) to minimize the “free energy” (the biological grounding of prediction error in Active Inference theory, cf. [Friston \(2010\)](#)) between its prediction and the actual world state. In our simulation, this means choosing an

action that makes the KG_i predicted consistent with the external situation.

Your prediction is that the control structure modifies informal gatherings. To make this prediction a reality and maintain a coherent experience, which action from the set of possible behaviors should you select?

- **LLM Action Selection:** The LLM selects the most coherent action. For instance, it generates a new individual:
 1. `Pachira Approaches Fountain Behavior` (edtype: `enhenBehavior`, rdfs:label "Approaches central fountain for social interaction").
- **Knowledge Graph Update (KG_{tl}):** The loop is closed by updating the main knowledge graph with the outcomes of the inference cycle.
 1. **Action Enactment:** The selected action is formally added to the KG and linked to the agent and the experience, creating a record of their enacted choice: `pachira.ModernLinearis.Generic.enhenInfluentialBehavior` `pachira.ApproachesFountain Behavior`.
 2. **Belief Update:** Because the agent acted to confirm its prediction, the predicted states are now inferred.

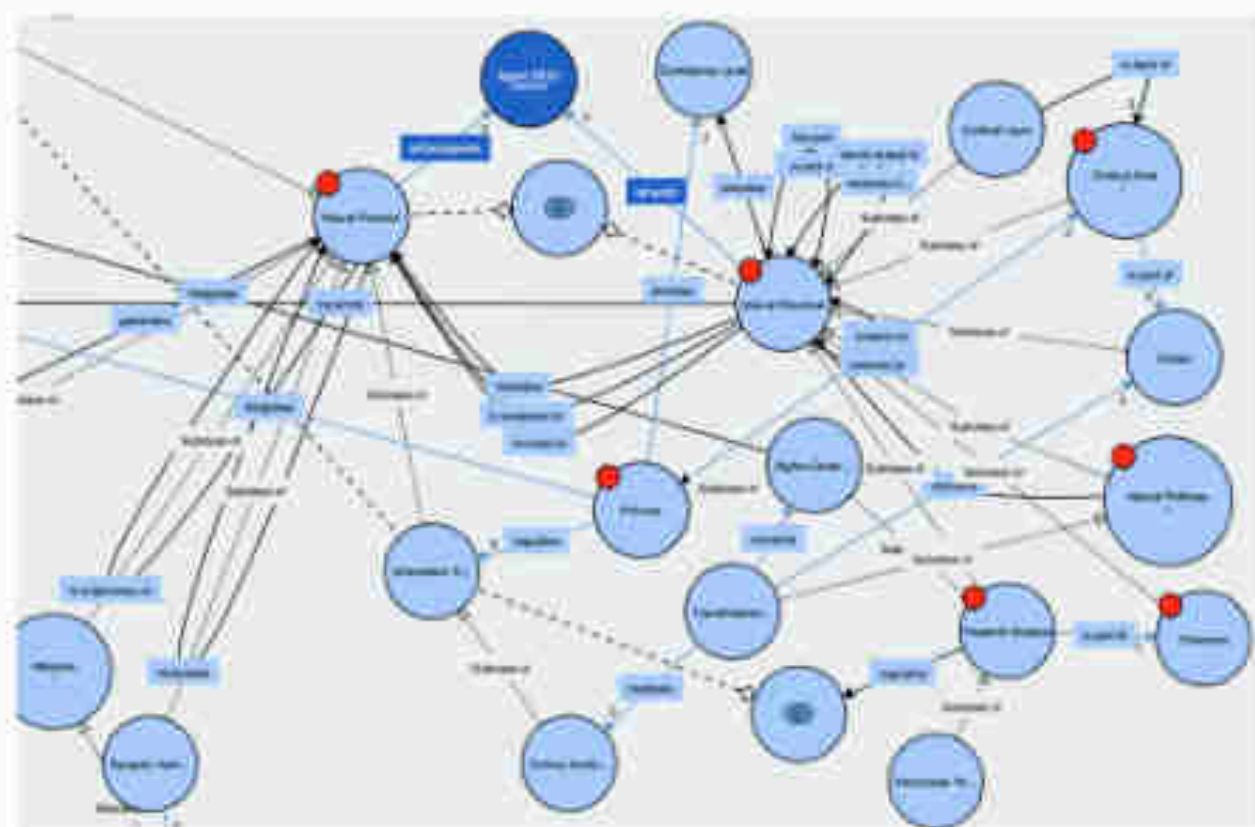


FIGURE 5
 2025 Agents and their relationships in subtypes of processes.

with high confidence. The belief involves Properties in *pachino-PachinoExperience_2025* are updated to include the newly confirmed affordance and social patterns.

- *pachino-Pachino_Experience_2025* belief involves Affordance: *pachino-EA_Informal Gathering Affordance_2025*.
- *pachino-Pachino_Experience_2025* belief involves Social Patterns: *pachino-SF_Informal Gatherings Situation_2025*.

This updated KG₁₁ now serves as the starting point for the next simulation cycle. This neurosymbolic loop provides the 4E (*embodied, embedded, enacted, extended*, cf. Newen et al. (2018)) cognitive grounding: the KG represents the embedded context, the LLM simulates the predictive brain of the embodied agent, and the cycle of prediction-action-update models the enacted coupling between them, making the tacit knowledge of dynamic environmental experience explicit. For the extended aspect, see Section 6.

The dynamic simulation flow, which models the agent's enacted cognition, reflects the structured stratification of concepts within our ontologies. To understand how the agent's high-level thoughts and behaviors are grounded in low-level neural mechanisms, it is essential to map the relationships between these different levels of description. Table 1 provides a detailed breakdown of

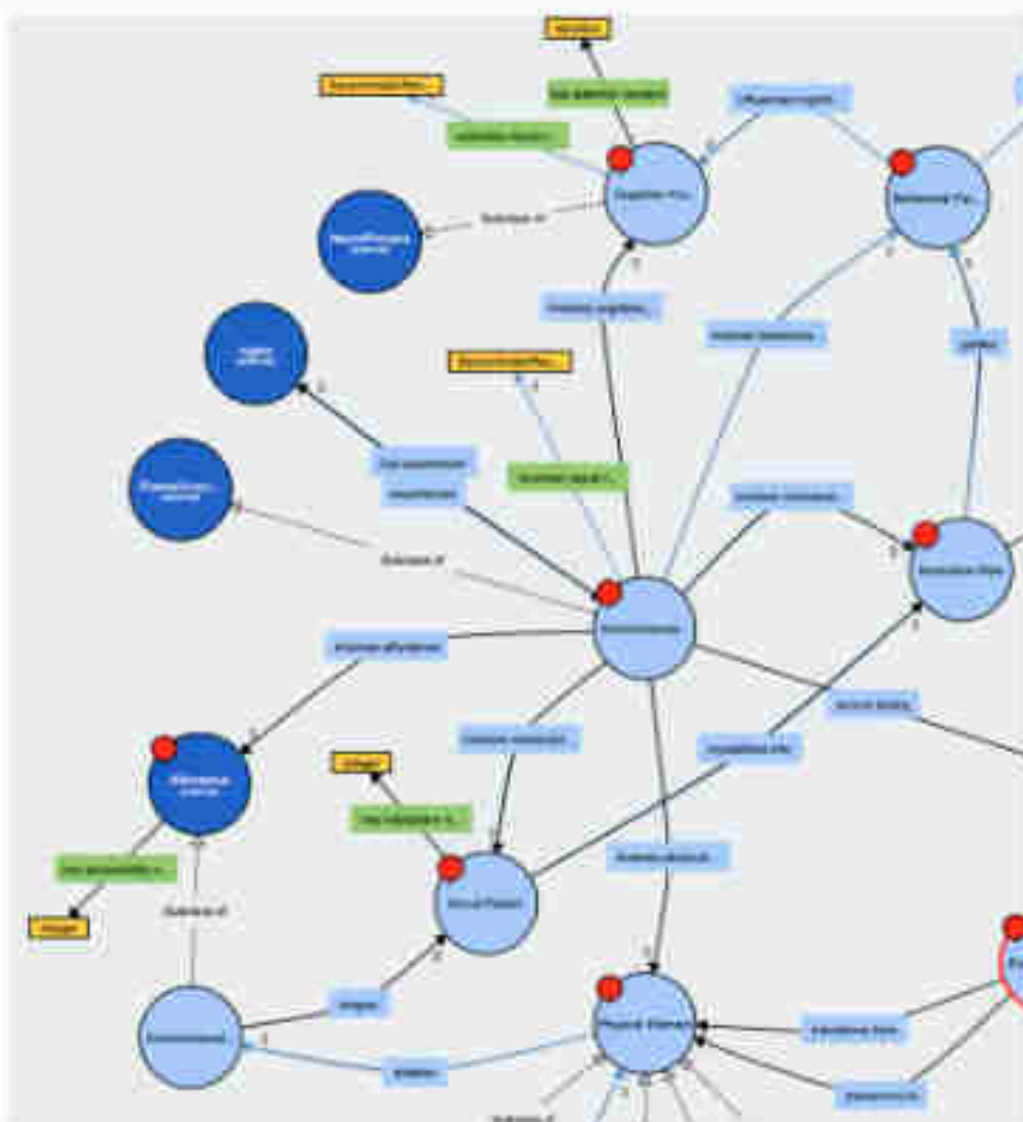
this mapping for each of the seven layers, showing how a high-level component like a social pattern is implemented at the neural level. Table 2 then distills this into a summary of the most crucial conceptual pairs—like Situation/Brain State and Action/Motor Command—that form the core of this multi-scale active inference model.

6 Extended reality interfaces

Concerning the extended aspect of 4E, REACON can be translated into immersive technology, moving from analytical understanding to a practical application. An eXtended Reality (XR) interface can transform multi-layer representation into lived experience, enabling stakeholders to perceive and interact with the multiple dimensions of environmental influence in real-time.

6.1 System architecture

An XR architecture should balance sophisticated analytical capabilities with user accessibility, employing state-of-the-art hardware components integrated through a unified software framework. The hardware foundation centers on advanced smart glasses incorporating high-resolution micro-OLED displays that minimize eye strain during extended use. Stereo cameras



881. *Stylosanthes* *degeniana* Schrad., with *Stylosanthes* *littoralis* and local *Stylosanthes* *affinis*.

provide environmental tracking with sufficient precision for accurate overlay registration, while LIDAR sensors enable precise depth mapping essential for correct spatial positioning of virtual elements. Eye-tracking sensors serve dual functions, both providing contextualized information delivery based on gaze direction and gathering data about visual attention patterns for validation.

The proposed implementation integrates predictive capabilities with immersive simulation technologies. This enables proactive design optimization and real-time assessment of environmental modifications, moving beyond descriptive research toward prescriptive design tools that can actively improve urban environments for human wellbeing. The integration of augmented reality technologies could represent a significant advancement over current methodological approaches, providing unprecedented opportunities for both research and practical application in

urban design and planning contexts. Here, the idea is to integrate BEACON into wearable technologies like the AR glasses equipped with

- Camera, to allow users to capture pictures based on an egocentric vision
- Audio with bone conduction, to receive a private verbal communication that guarantees the privacy
- Eye-Tracker, to provide contextualized information in real-time

The following workflow presents a schematic representation of the integration between BEACON and wearable technologies starting from users' perspective (Figure 9).

The picture below (Figure 4) shows the application through smart glasses technology, where different analytical layers are

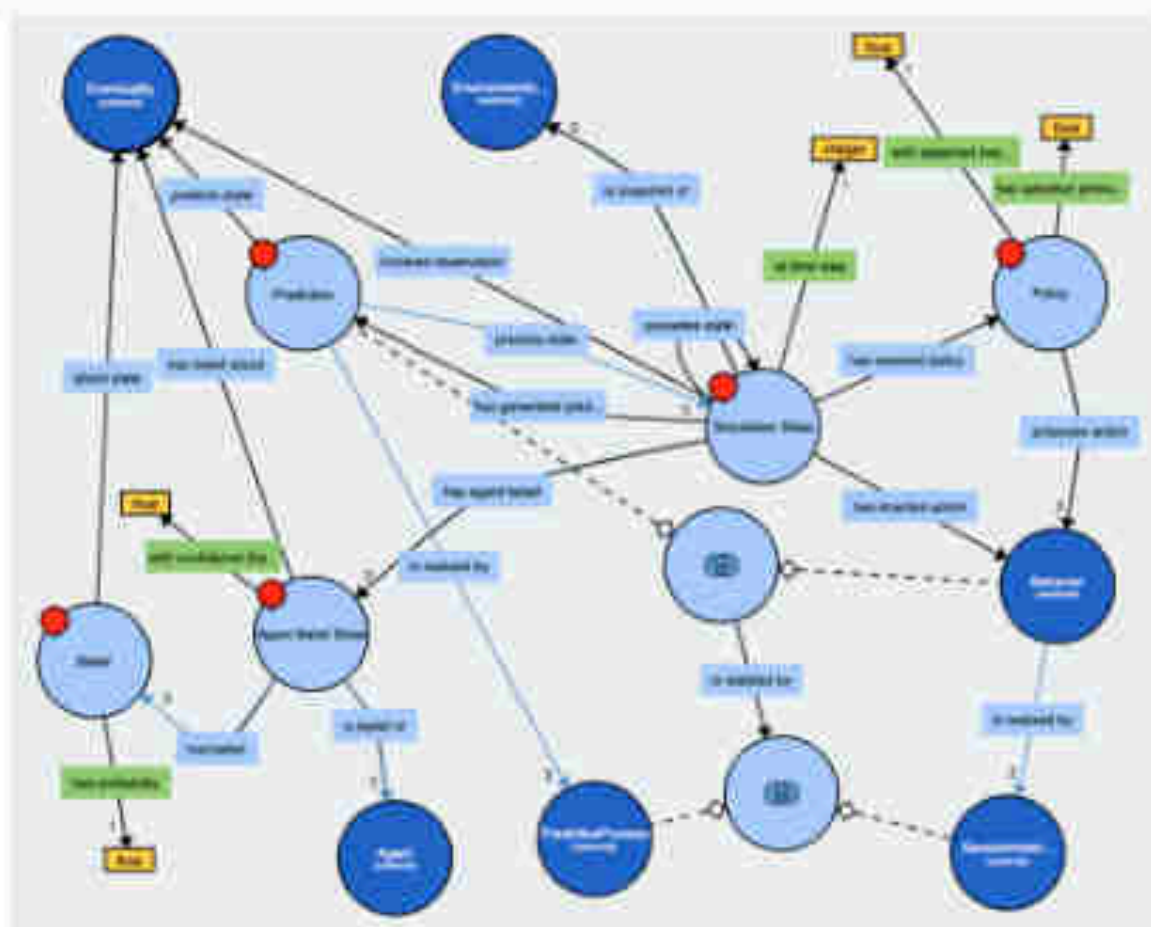


FIGURE 1
 1994. Average total catch (kg) of blue crabs (*Callinectes sapidus*) in the Chesapeake Bay, with total catch (kg) and catch per unit effort (kg/ha) for each month.

superimposed into the real-world environment, based on the eye-tracker records. The implicit and explicit knowledge will be shared using verbal communication (audio system). The integration of ear-free conducting audio ensures private communication while maintaining environmental awareness, allowing users to receive detailed aural information without disrupting their natural spatial experience or social interactions with others in the space.

Our system moves beyond static analysis to offer dynamic, context-responsive insights that adapt to individual users and changing environmental conditions.

Through this implementation, users gain a comprehensive understanding of urban environments across multiple analytical dimensions simultaneously.

7. Discussion

The multi-layered ontological framework presented in this study is both a theoretical advance and a practical tool for understanding and optimizing built environments. Its development and application can reveal insights extending neuroarchitecture to broader questions about human-environment interaction, interdisciplinary integration, and the role of technology in urban planning.

7.1 Theoretical contributions

BEACON advances neuroarchitecture theory with the systematic integration of seven analytical layers and moves beyond the fragmented approach characteristic of much environmental psychology research. Rather than studying isolated variables—lighting conditions, spatial configuration, or material properties—in isolation, it facilitates the extraction of how these elements interact systematically to produce emergent effects. This systemic perspective aligns with contemporary understanding of complex adaptive systems while remaining grounded in empirical neuroscientific research.

The interdisciplinary bridge across layers addresses a challenge in environmental research: the integration of objective measurements with subjective experience. By tracing pathways from measurable physical properties through experiential affordances to neural activation patterns, BEACON provides a conceptual structure for understanding how objective environmental features produce subjective experiences. This integration draws on Gibson's ecological psychology, Alexander's pattern language, and contemporary neuroscience to create a unified analytical approach.

The formal ontological specification enables computational reasoning about environmental-human relationships, transference

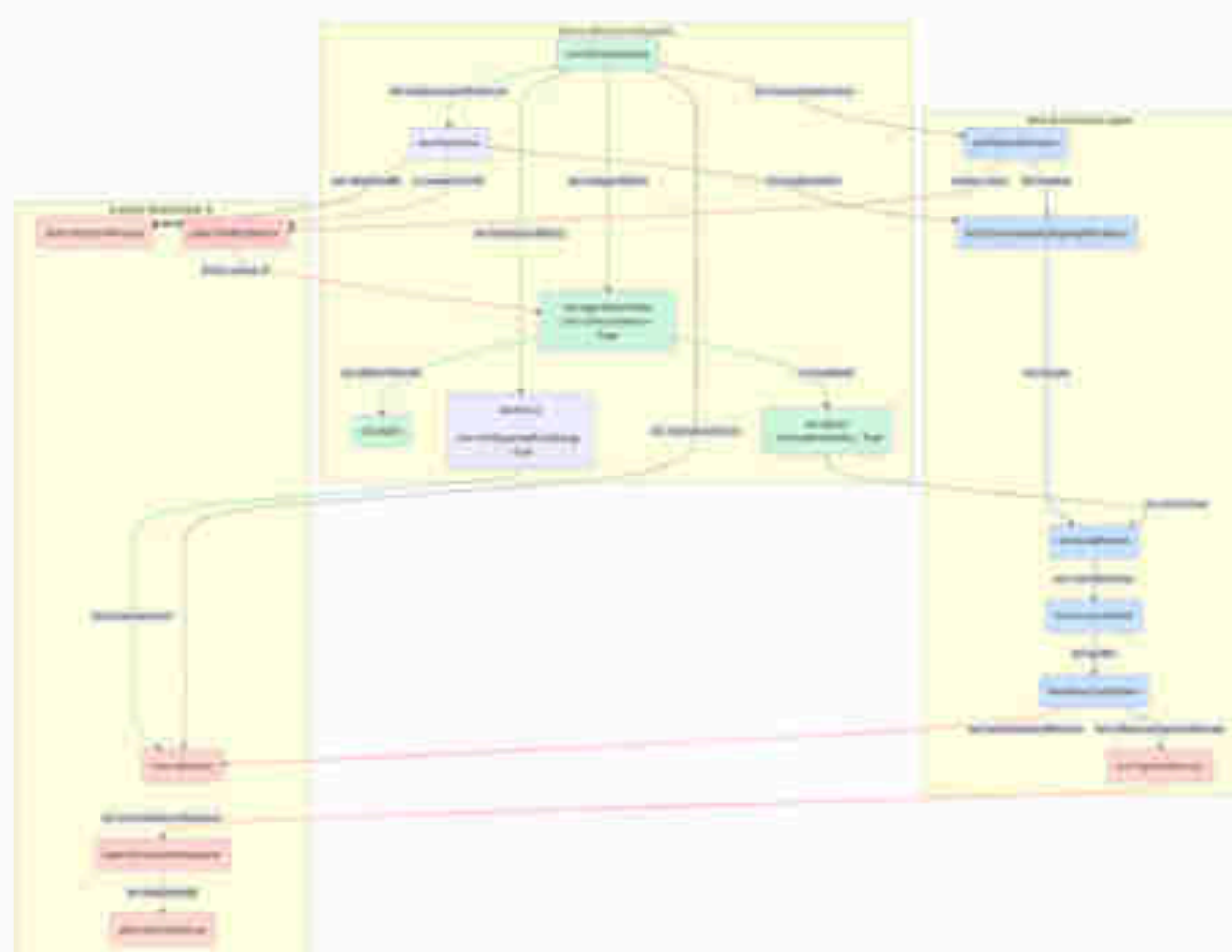


FIGURE 1 BEACON Predictive model maps input behavioral and physical data from various sources including observations of specific designed physical elements, which analyze affordances that these spatial patterns eventually produce by high-level predictions. Predictions, when used with updates of belief states about social patterns that can crystallize into normative rules guiding behavioral patterns influencing cognitive processes. Simulation makes select policies resulting actions leading to computational behavior of behavioral patterns that in turn produce environmental responses modeled by neural pathways.

informal observations into logical structures amenable to automated analysis. This formalization serves multiple purposes beyond enabling XR implementation. It provides a precise vocabulary for interdisciplinary communication, reducing misunderstandings arising from disciplinary differences in terminology. The ontological structure enables systematic comparisons across case studies, identifying universal patterns while accommodating cultural variation. Perhaps most importantly, it creates a foundation for accumulating knowledge over time, with new findings integrated into the existing structure. BEACON's formal treatment of temporal dynamics represents another contribution by incorporating multiple timescales—from immediate perceptual responses to generational changes in spatial culture.

7.2 Practical implications

BEACON's practical applications extend across multiple domains of environmental design and urban planning. In urban planning

contexts, the ability to predict how design modifications cascade through social and cognitive layers enables evidence-based decision-making. Planners can evaluate proposals not merely for traffic flow or economic impact but for their comprehensive effects on human wellbeing. The Potsdam case study simulates how seemingly minor modifications—replacing trees with planters, changing lighting systems—may create cascading effects through all analytical layers.

Heritage preservation gains new analytical tools for understanding and communicating the significance of historical environments. Beyond preserving physical fabric, the framework reveals how historical spaces enabled social relationships and shaped community consciousness. This deeper understanding can inform preservation strategies that maintain not just buildings but the experiential qualities that made spaces meaningful to their communities. The AR implementation enables immersive heritage interpretation that conveys this multilayered significance to contemporary audiences.

Therapeutic design applications emerge from explicit connection between environmental features and neural responses. Healthcare facilities can be optimized not through intuition but

TABLE 1 Detailed bridging across the seven layers by mapping between the high-level, symbolic concepts of experience and their underlying neurophysiological implementations.

Layer (from S&L)	Cognitive/Behavioral stratum (The "what")	Bridging property/Mechanism	Neural stratum (The "how" - EEG/MEG grounding)
1. Percept	A symbolic representation of a real-world object or event, e.g., the victim PP, <i>Characteristics</i> (Koch, 1998)	what-what	The physical event is transduced into the electrochemical signals of the sensory nervous system
2. Experiential	The agent's recognition of a meaningful opportunity for action, e.g., the victim PP, <i>Characteristics</i> (Koch, 1998)	beliefs/attention/through	The information is recognized by e.g., the P1/P2 components, which involves the brain integrating sensory signals with predictions
3. Social	The agent's inference of an abstract social situation, e.g., the victim PP, <i>Characteristics</i> (Koch, 1998)	beliefs/social context	This high-level social inference corresponds to a specific set of neural activity patterns in brain regions associated with social cognition
4. Normative	A shared belief about "normal" behavior in a given context, e.g., the victim PP, <i>Characteristics</i> (Koch, 1998)	what-what/through	The rule is recorded as a strong prior within the agent's generative model, represented by a specific set of neural activity patterns
5. Behavioral	A belief, intention, and goal-directed action in the world, e.g., the victim PP, <i>Characteristics</i> (Koch, 1998)	what-what/through	The observable behavior is the emergent result of a sequence of low-level electrochemical processes (e.g., patterns of neural commands)
6. Cognitive	A discrete, high-level mental event, like a "change of mind" (e.g., belief update) or a moment of focus (e.g., cognitive focus)	what-what/through	This cognitive event is precipitated by the accumulation of many underlying electrochemical signals, which drive synaptic plasticity and belief updating
7. Neural	The direct, subjective feeling associated with a mental event like "what is like" to have that response	what-what/through	The victim PP, <i>Characteristics</i> (Koch, 1998). This is the foundational neurophysiological event

TABLE 2 Summary of key stratified concepts: the core conceptual pairs enabling the representation of the multi-scale active inference model.

High-level concept (Cognitive/Behavioral stratum)	Bridging property	Low-level implementation (Neural stratum)	Description of bridge
The Situation (Beliefs/Social Context)	beliefs/social context	The Brain State (Electrochemical Patterns)	A high-level, abstract social situation is encoded as a specific pattern of physical brain activity
The Prediction (Int. Prediction)	what-what/through	The Predictive Machinery (Cortical Predictive Processes)	A conceptual prediction about the future is the emergent result of the underlying neurochemical machinery of predictive coding
The "Aha!" Moment (Belief Update)	what-what/through	The Focus Signal (Cortical Predictive Processes)	A conscious change of belief is triggered by the accumulation of low-level neural signals indicating a mismatch with reality
The Action (Behavior)	what-what/through	The Motor Command (Cortical Motor Output Patterns)	A meaningful, goal-directed action is physically realized by a complex sequence of neural motor commands

through systematic analysis of how design elements influence stress, attention, and emotional regulation. BEACON's grounding in neuroscience provides empirical justification for design decisions that might otherwise seem subjective. Educational environments benefit similarly, with classroom designs optimized

for sustained attention and positive emotional associations with learning.

BEACON may also enable community empowerment through environmental literacy. By making visible the usually hidden influences of built environments, communities may become more

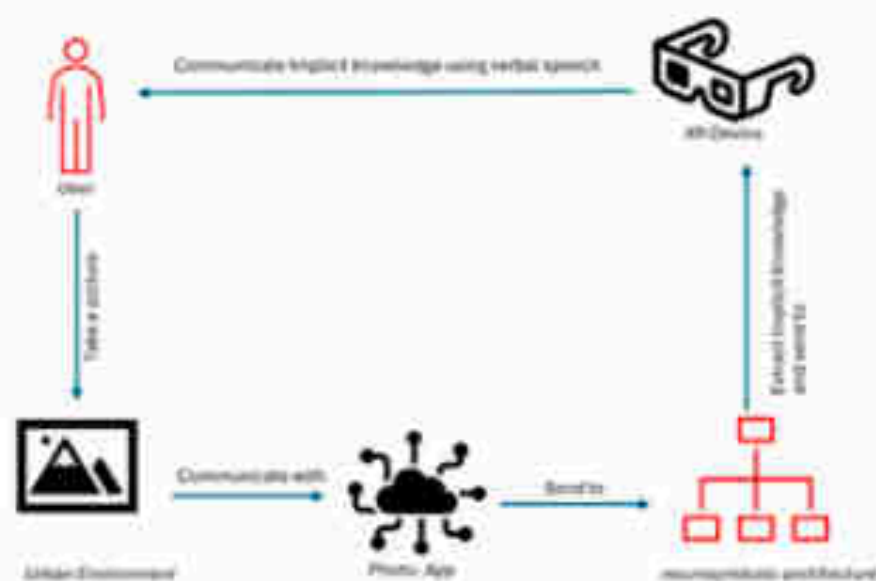


FIGURE 19
A schematic representation of the interplay between EEM, City and wearable technology.



FIGURE 20
A practical application of BEACHON through smart glasses technology. The red highlighted area identifies the Physical Layer, focusing on the Chiesa Madre's architectural elements; The green highlighted area represents the Experiential Layer, encompassing the outdoor dining and social gathering area; The yellow highlighted area indicates the Social Layer, focusing on access patterns, mobility dynamics, and areas for social interaction within the scene.

aware of their personal and social effects. The AR implementation may be useful in this regard, transforming abstract concepts into immediately perceivable experiences that facilitate public discourse about environmental quality.

7.3 Methodological innovations

Our approach introduces several methodological innovations that contribute to environment behavior research.

The “Mixture of Experts Simulation” method used to elicit negotiated requirements for BEACON design offers a model for interdisciplinary collaboration in complex domains. By structuring expert interaction around specific inter-layer relationships, the method enables knowledge integration while respecting disciplinary expertise.

The formal ontology network provides a shareable conceptual basis for semantic and data interoperability, and can be evolved in a transparent way. It also provides a conditioning ground for LLMs, leaving room for dynamic tacit knowledge extraction and modular ontology extension (Di Giorgio et al., 2023).

BEACON’s predictive capabilities enable hypothesis testing before implementation. It can also reduce costly mistakes in urban development while identifying beneficial interventions.

7.4 Limitations and future directions

Besides these contributions, some limitations warrant acknowledgment.

While BEACON supports various user types, its intended use within different communities of practice needs adaptation considering the different backgrounds and levels of expertise. Anyways, the neurosymbolic knowledge-driven methods are supposed to be not necessarily in the foreground of final users’ applications.

BEACON’s comprehensive analysis requires extensive data collection that may prove resource-intensive for routine application. Data collection and its reverse engineering, as well as the evaluation methods of knowledge graphs depend on specific tasks and reasoning habits within specific communities, which need to be tackled on purpose.

While the XR implementation can operate with limited data, realizing its full analytical potential requires multimodal documentation across extended time periods. Future research should develop streamlined assessment protocols that capture essential information with reduced resource requirements to deal with rising costs. There are other limitations like technological barriers and uneven access across different regions, which might be mitigated in future technological infrastructures, and provisionally accommodated by using more traditional devices.

Cultural variability in spatial interpretation presents ongoing challenges. While BEACON’s structure appears universal, the specific meanings associated with spatial configurations vary significantly across cultures. The elevated religious building that signifies authority in Catholic Sicily might convey different meanings in Buddhist Thailand or secular Sweden. Future development should incorporate cultural calibration mechanisms that adjust interpretations while maintaining structural consistency.

Incorporating neural and cognitive data into urban design raises ethical issues (e.g., surveillance, data ownership, cognitive profiling), which will require cybersecurity solutions and adherence to local regulation, e.g., GDPR and AI Act in the EU.

Empirical validation across diverse contexts remains incomplete. While the Pichino case study demonstrates analytical and simulation power, validation across different cultural contexts, urban scales, and building types is needed. Experimental studies manipulating specific environmental features while measuring responses across all seven layers could refine understanding of inter-layer relationships.

8 Conclusion

This paper has presented a comprehensive multi-layer ontology network, BEACON, that bridges the gap between neuroscientific research and practical urban design. Through systematic connection of physical design elements to neural responses via intermediate layers of experience, social dynamics, normative regulation, behavior, and cognitive processing, we provide both theoretical understanding and practical tools for creating human-centered urban environments.

Starting from a theoretical integration of requirements to analyze environmental influence while maintaining fidelity to empirical research findings, BEACON has been formalized in the OWL knowledge representation language for computational reasoning. The Pichino case study applies BEACON modeling to demonstrate how architectural design functions as social engineering, shaping not merely behavior but the neural architecture of inhabitants across generations. The augmented reality implementation transforms abstract analysis into immersive experience, enabling diverse stakeholders to perceive and understand multiple layers of environmental influence.

As global urbanization accelerates, the need for scientifically-informed, human-centered design intensifies. BEACON provides the integration of formal ontology, neuroscience, and immersive technology offering a new hybrid paradigm in urban design to recognize built environments as active participants in shaping human experience.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repository(s) and accession number(s) can be found below: <https://github.com/alekogargano/builtenvironment>.

Author contributions

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Acharya, D. R., Kappas, E., and Iriem, R. (2023). Agentic AI: tomorrow's intelligence for complex tasks. *A comprehensive survey*. *IEEE Access* 11, 10912–10938. doi:10.1109/ACCESS.2023.3332814
- Adolphs, R. (2019). What does the amygdala contribute to social cognition? *Ann. N. Y. Acad. Sci.* 1462, 42–64. doi:10.1111/nyas.14062
- Alexander, C. (1977). *A pattern language*. New York: Architectural Association, Oxford University Press.
- Alexander, C. (1979). *The timeless way of building*. Oxford University Press.
- Alexander, C. (2003). *The nature of order*. Volume 1: the phenomenon of life. Center for environmental structure.
- Atkins, J. A., Blanton-Iliut, D. A., Oliver, J., Bostrom, A., Margolis, P., and Alexander, R. (2021). Cities and neuroscience research: a systematic literature review. *Front. Psychology* 12, 691322. doi:10.3389/fpsyg.2021.691322
- Batali, M., Hertz, J., Yehoshua, S., and Greenberg, N. (2021). Walking through architectural space: the impact of attitude being on human brain dynamics. *Front. Phys. Neurosci.* 15, 675. doi:10.3389/fnui.2021.675477
- Baym, M. (1996). *Audiotext navigation and architectural design*. London: E and FN Spon.
- Bian, J. X., and Mattson, R. D. (2013). The neural basis and neural-coded information processing in the human striatum. *Wiley Interdiscip. Rev. Cognitive Sci.* 4, 61–75. doi:10.1002/wics.1286
- Bischoff, E., Powers, V., Daga, E., and Gangemi, A. (2019). "Experimenting with different design" in *In the international conference on knowledge engineering and knowledge management*. Berlin, Heidelberg: Springer Berlin Heidelberg, 128–144.
- Braden, A. A., Kozak, N. H., Silligars, N. A., and Taylor, R. P. (2022). What happens to your brain when you walk down the street? Implications of architectural proportions, topology, and fractal geometry for urban science. *Urban Sci.* 6, 111. doi:10.3390/urban6010061
- De Gennaro, S., Malyugin, A., and Rizzo, A. (2023). Neurocognitive graph enrichment for grounded world models. *In: Process. and Manag.* 61, 161–184. doi:10.1016/j.pro.2023.104127
- Dolan, J., de Saint Aubert, J. B., Katsamaki, E., Balle, M., Gehrig, L., Bögg, M., et al. (2022). Mobile translocus imaging of lamina II-based integration with high-density EEG. *Eur. J. Neurosci.* 54 (12), 4296–4304. doi:10.1523/JNEUROSCI.1519-22.2022
- Dubajic, E., Jones, G. B., Pankaj, J. L., and Greenberg, N. (2022). Neuroscience and architecture: modeling behavior through subconscious responses in the built environment. *Neurosci. and Biobehav. Rev.* 138, 104711. doi:10.1016/j.neubiorev.2022.104711
- Foran, M. (1979). "Part three: discipline" in *Discipline and practice: the birth of the person*, 115–225.
- Heur, R. (2010). The free energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 427–438. doi:10.1038/nrn2787
- Hopcroft, A., and Hertzberg, A. C. (2021). Logic augmented generation. *J. Nat. Comput.* 41, 10019. doi:10.1016/j.jnuc.2021.10019
- Gibson, J. J. (1977). *The ecological approach to visual perception*. Houghton Mifflin.
- Hirakawa, A. R. (2024). Applications, opportunities and ethics of the extended reality in urban design and planning. *J. American Plan. Assoc.* 60 (3), 313–327. doi:10.1080/03944655.2023.227123
- Hill, J. T. (1996). *The hidden dimension*. Garden City, NY: Doubleday.
- Hofler, P., Gangemi, A., and Janssen, K. (2016). Ontology engineering with ontology design patterns. *Foundations and applications* (Berlin, Heidelberg, 25).
- Jones, G., and van Boven, M. (2016). Selective neural representation of abstract elements for navigation. *Nat. Neurosci.* 19, 673–677. doi:10.1038/nn.4257
- Joffe, R. (2019). Urban architecture: a cognitive neuroscience perspective. *Design J.* 22 (6), 850–871. doi:10.1080/14606807.2019.1625886
- Kaplan, S. (1977). The cognitive benefits of nature viewed as integrative framework. *J. Environ. Psychol.* 15 (3), 189–192.
- Karadimitriou, A., and Taylor, L. (2017). Architecture and neuroscience: what can the EEG recording of brain activity reveal about a walk through everyday space? *In: J. Environ. Psychol. Distributed Soc. Sci. (Engel.)* 15, 554–565. doi:10.1080/13445760.2017.1380880
- Koch, S. G., and Wolff, M. (2022). Neuroscience and the cities: neuroscience Goes Urban. *In: Soc. and Urban Geogr.* 46, 285–301.
- Kölsch, S., and Gallinat, J. (2021). Environmental neuroscience unravels the pathways from the physical environment to mental health. *Nat. Rev. Psychol.* 2 (3), 263–285. doi:10.1038/s41577-021-00117-0
- Lee, S., Shin, W., and Park, S. J. (2022). Implications of neurocognitive for the experience of the built environment: a scoping review. *Archaeo-Sci. Soc. J. Archaeol. Soc.* 18 (2), 125–144. doi:10.1080/ARCS.18.49.2021.1760094
- Mahdavi, A., Wolkstein, D., and Hagen, C. (2018). *Tensor2Tensor: (beyond) statistical framework for the representation of inhabitants in building performance computing*. *J. Build. Eng.* 15, 100644. doi:10.1016/j.jobe.2017.100644
- Margulies, G., and Eick, S. (2014). The built environment and the brain: issues of mapping methods to investigate the impact of housing architectural design. *J. Environ. Psychol.* 40, 103–128. doi:10.1016/j.jenvp.2013.09.002
- Melamed, A. (2020). Neuro-cognitive architecture: buildings and city design that inspired to human cognition, cognitive states. *Rev. Urbanization* 6, 100122. doi:10.1016/j.rururb.2024.100122
- Mosconi, E. F., Becken, K., Fekken, E., and Chakrasan, Y. (2022). Parallel pathways provide topographic spatial information to prefrontal cortex. *J. Neurosci.* 42 (1), 89–97. doi:10.1523/JNEUROSCI.0946-21.2022
- Naseed, H., Elahi, A. U., Qiu, Y., Saifi, M., Arwan, S., Daman, M., et al. (2023). A comprehensive overview of large language models: AI's revolution in intelligent system and technology.
- Neven, A., Gallinat, J., and De Baat, L. (2019). AI: Cognitive Architectural Design: Design and Control Issues.
- Oh, H., White, M. F., Wheeler, B. W., Bethel, A., Ullmann, G. C., Nishikawa, V., et al. (2016). Attention selection theory: a systematic review of the attention selection process of exposure to natural environments. *J. Environ. Psychol.* 52 (1–2), 303–341. doi:10.1016/j.jenvp.2016.11.003
- Rao, T., Brown, E., and Petrucci, G. (2024). Generative models for sequential dynamics in active systems. *Cogn. Neurosci.* 16 (4), 3219–3222. doi:10.1080/17513757.2023.2266024
- Rolani, M. (1996). *The neural dimension*. University of Chicago Press.
- Tran, V., and Gangemi, A. (2016). "Twin-DMS ultimate and its core ontology design patterns" in *Ontology Engineering with Ontology Design Patterns*. Berlin, Heidelberg, 91–103.
- Rod, P. B., Belchick, F., Yehoshua, S. A., Ghann, H., Zohar, E., and Luchini, R. (2023). Engineering methodological approaches of experimental studies in the field of neurocognitive: a systematic review. *IEEE/ACM Trans. Comput. Sci.* 34 (2), 284–308. doi:10.1177/19479642231153123
- Rothman, C. K., and Cyphert, D. D. (2006). Walking through downtown: using mapping, urbanism models and experimental space. *Memory & Cognition* 34 (1), 1130–1138. doi:10.3758/BF03193241
- Rothman, C., and Vignola, U. (2014). The urban system system. *Urban Res. Monitor.* 27, 168–182. doi:10.1186/s13656-014-0020-1
- Russett, J. A. (1999). A computer model of affect. *J. Personality Soc. Psychol.* 76 (4), 1161–1178. doi:10.1037/0022-3514.76.4.1161
- Silagowski, N. A. (2024). Architectural knowledge: making a knowledge system, the problem space of building environments that promote health and well-being. *Nat. Rev. Urban Sci.* 10, 291–298. doi:10.1038/s41577-024-0254-1

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- Schlegelm, K. A. (2025). Using geometry to solve and Alexander's 12 fundamental properties. *Revised the architect studies*. *Proc. Arch Sci.* doi:10.1016/j.pro.2025.01.002
- Saxe, R., and Kanwisher, R. (2003). People finding short finding short people: the role of the superior parietal sulcus in theory of mind. *NeuroImage* 19, 1833–1842. doi:10.1016/S1053-8100(03)00230-4
- Twiss, R. M., Mondadori, A., Gerschlager, V., Williams, C., Higgins, M., Toga, V., et al. (2013). A map for social navigation in the human brain. *Neuron* 82, 235–243. doi:10.1016/j.neuron.2013.06.011
- Uguzoglu, Y., Xu, H., Choudhury, G. A., Goren, M. C., Sharpen, A., and Li, X. (2024). Towards next-generation urban disaster support systems through AI-powered construction of scientific knowledge using large language models: a case in optimizing internal freight transportation. *Smart Cities* 7 (5), 2302–2413. doi:10.3389/fnagi.2025.1674007
- United Nations (2018). *World Meters*. Available online at: <https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html>
- Wang, F., Sanchez de Olave, G., Daffour, Z., and Gauthier, R. (2022). The methodology of architectural expertise: a methodological perspective on neuro-architecture. *Front. Hum. Neurosci.* 16, 833328. doi:10.3389/fnhum.2022.833328
- World Wide Web Consortium (W3C) (2015). *T web ontology language document overview*. W3C Recommendation.
- Yehia, A. L. (1987). *For architecture and more*. New York: Plenum Press.



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On situated affectivity and the orchestration of brain-body-environment rhythms

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An increasing number of studies in cognitive science challenge traditional views that position the brain as the exclusive or central mechanism of cognition, particularly those that frame it as a standalone computational unit. Understanding cognition as emerging through brain-body-environment relationships necessitates moving away from disembodied accounts of the mind and the “computer” metaphor of the brain, which oversimplifies the process by which cognition arises. An alternative view is that of a resonating brain-body system that can become attuned to the different rhythms of the (built) environment. This implies a capacity to actively sense and attend to subtle differences perceived through sensorimotor and affective engagement. This perspective article builds on the idea of natural attunement to environmental rhythms and examines it in relation to affectivity. Specifically, it integrates insights from current work on situated affectivity with non-representational concepts associated with the notion of rhythm to identify future direction for research and architectural design. The emerging themes challenge traditional approaches highlighting an often-overlooked aspect in studies of cognition and architecture: how events in the body, brain, and surrounding environment change over time.

KEYWORDS

situated affectivity, affective scaffolding, attunement, environmental rhythms, resonance, enactive cognition, atmospheres, architectural experience

1 Introduction

There is a growing recognition that brain and body rhythms (e.g., breathing, circadian rhythms) are often engaged in coupling processes and dynamic coordination, influencing how we perceive and evaluate our environment (Varga and Heck, 2017; Klimesch, 2018; Kutz et al., 2018; Coatsworth et al., 2020; Klimesch, 2018) argues that the body-brain can be conceived as a single rhythmic, hierarchical system since the coordination of body-brain oscillations (e.g., lung-heart couplings) involves different frequencies that follow specific coupling principles. According to Marzocchi (2024), the hierarchy of brain-body rhythms, where slower bodily rhythms modulate faster neural oscillations, is closely linked to the experience of time. The coupling of multiple oscillations allows the brain-body system to track bodily and emotional changes across multiple timescales, providing a temporal organizing mechanism. Crucially, these processes are sensitive to affective states: physiological rhythms such as heartbeat, easily modulated by arousal, can expand or contract subjective time (Ellen et al., 2006; Daut-Valet et al., 2011), which reflects the

ability to adjust and synchronize with external rhythms and collective activity (Orús-Viñet and Gil, 2009). Thus, as *Brazaitis (2023)* argues, time is a relational measure of change, grounded in events within the brain, the body, and the surrounding environment. Accordingly, rhythmic coordination of different oscillations is not confined to an individual's physiological boundaries. It extends beyond the skin, influencing and being influenced by interactions with the environment. Evidence suggests that respiratory rhythms, for example, modulate neural oscillations, influencing perceptual, affective and cognitive dimensions (Varga and Heck, 2017; Heck et al., 2019; Herten et al., 2022). Yet, internal factors can also influence such brain-breathing couplings (Gibson et al., 2024). Therefore, it is unreasonable to assume that body-brain rhythms function independently of external rhythmic phenomena, as empirical evidence suggests that dynamic coupling plays a role in their orchestration (Chiriac-Bouché and Dyballa, 2023; Northoff et al., 2021).

Ecological-enactive approaches to cognition (Gibson, 1979; Michaels and Carello, 1985; Varela et al., 1992; Gallagher, 2009; e.g., Warren, 2006) and the notion of direct perception bring to the foreground phenomena associated with dynamic couplings (e.g., coordination, resonance) and relational structures that enable such couplings. From this perspective, perceiving, acting, and knowing are emergent properties of the agent-environment system, shaped by continuous interactivity with external rhythms and affordances. For instance, the self-organizing phenomenon of antinociceptive dynamics (Thelen et al., 1987; O'Regan and Noë, 2001) as the cyclical perception-action coupling process is a key concept to understanding how we interact and detect environmental information (Dyballa et al., 2018; Dyballa et al., 2022). The agent's movement, including body parts, is shaped by sensory stimulation across modalities that co-occur in reciprocally interacting cycles. Sensorimotor dynamics are sensitive and responsive to salient environmental features, rich in value and meaning, presenting opportunities for action, commonly referred to as affordances (Gibson, 1979).

The concept of affordances rooted in ecological psychology, has evolved into an interdisciplinary framework (see Dyballa, 2022). Recent refinements include a relational perspective that considers the interaction between the agent's abilities and environmental features (Chemero, 2009), and an experiential view conceiving affordances as a field of possibilities that become salient in a given context, shaped by objects, people, and situational dynamics (Van Dijk and Rietveld, 2016). Affordances specific to a particular situation or place (e.g., classrooms, street parks) contribute to the emergence of collectively generated higher-order relational structures, known as behavior settings¹, which have specific spatial and temporal boundaries (Holl, 2024). These structured patterns of coordinated behavior, tied to specific settings, invite and sustain individuals' engagement. Active engagement with environmental features and tendencies to move or act in particular ways, both individually and collectively, are

closely linked to how the agent's environment affords specific actions and behaviors (Gendo et al., 2012; Reimer and Epstein, 2017; Dyballa et al., 2019; Dyballa et al., 2021) and affective states (Frijda, 2004; Giffers, 2014; Colombetti, 2017). For instance, atmospheres are considered extra-individual phenomena that shape the salience of affordances (Garrá, 2024) and invite an individual's affective engagement. The perception of relevant (affective) affordances is an active process involving the appraisal of meaning-laden environmental cues. As [Rietveld and Kruiger (2014), p. 14] describe it, "[...] is a process of perceiving a value-rich ecological object", a dynamic interplay of evaluation, adaptation, and sense-making. [Holl (2024b), p. 188] further emphasizes the relational nature of the affordances, arguing that their value-laden properties are "realized in the anticipation of an action or the course of action". Therefore, affordances are not static properties of the environment but emerge through an agent's active interaction with their surroundings that occurs over time, shaping both behavior and affective experience.

Similarly, building on enactive and extended mind theories, Thompson and Stapleton (2009) argue that cognition is not confined to the brain or external structures but "is the relational process of sense-making that takes place between the system and its environment" (p. 4, emphasis added). The sense-making activity regulates our interactions with the world, transforming an otherwise meaningless physical reality into a "place of salience, meaning and value: an environment (Varela) in the proper biological sense of the term" (p. 25). In other words, cognition enables organisms to inhabit a world of significance. Crucially, this enactive perspective of sense-making implies that cognition is inherently affective. As [Colombetti (2024), p. 25] states, "one is affected when something merely strikes one as meaningful, relevant, or salient". Affective states, therefore, are integral to how we engage with the world. They manifest as psychological tensions that push an agent either away from (negative valence) or towards (positive valence) particular aspects of the environment. This fundamental tendency to modify one's relation with the environment (Colombetti, 2017) forms the basis for the concepts of affective scaffolding and affective niche (Colombetti and Krueger, 2015; Krueger and Colombetti, 2018), which describe how individuals shape their environments to regulate and sustain affective experiences.

Taken together, these perspectives highlight that cognition is not only relational and affective but also temporally structured through the couplings between brain-body rhythms and the environments we inhabit. To advance this line of inquiry, it is necessary to explore how situated affectivity intersects with the dynamics of the sociomaterial environment. This perspective article brings together current research and theory aiming to deepen our understanding of this relationship and to catalyze new directions for research. The discussion is framed through the lens of dynamic systems approaches to cognition² (Van Gelder, 1998; Thelen and

¹ The notion was first coined by Slater (1996) who observed that the behavior of different children in the same setting had less variability than the behavior of a single child across settings.

² The dynamic systems approach challenges current information-processing understandings of cognition and its connection with associations with the brain-scognitive materials. The approach emphasizes the role of cognition as "the simultaneously mutually influencing unfolding of complex temporal structures" (Van Gelder, 1998, p. 422).

Smith, 2006), which emphasize the dimension of temporality. The method combines ideas and findings from different fields, organized around *rhythm and temporality*. It draws attention to relational aspects that are often missed in stimulus-response models emphasizing the need to consider how processes unfold over time. The main contribution is to treat rhythm as a means of connecting brain, body, and environment, and to show how this view can guide future research and inclusive architectural design. The goal is to highlight overlooked aspects of affectivity and suggest new ways to study how agents and environments interact over time.

The discussion is organized into four sections. **Section 2** explores and compares the notions of *resonance*, *attunement*, and *entrainment*, examining how dynamic coupling processes unfold between the agent and the sociomaterial environment. **Section 3** foregrounds key aspects of situated affectivity by juxtaposing different perspectives on affective relationality, including affective affordances, affective scaffolding, affective arrangements, and atmospheres. Finally, **Section 4** synthesizes the main contributions from the preceding sections, highlighting emerging themes and implications for research and design, and **Section 5** concludes by summarizing key insights and suggesting directions for future investigation.

2 Shared brain-body-environment rhythms

The synchronization of brain rhythms with body rhythms and environmental rhythms is often linked to the notions of *resonance*, *attunement* and *entrainment*. Entrainment and resonance, at the level of agent-environment interaction, can be seen as measurable dynamic processes between agent and environment, while attunement describes the experiential quality often connected with these dynamics.

Resonance is a core property of perceptual and neural systems functioning across multiple scales: from the bursting activity of single neurons (Jahnke et al., 2003), through the spontaneous oscillatory dynamics of neuronal networks (Thompson and Vasilis, 2001; Varela, 1995), to the level of body-brain-environment coupling. In ecological psychology, the term refers to Gibson's metaphor of a *resonant brain*, rooted in the idea that "[...] the perceptual system simply extracts the invariants from the flowing array; it *resonates* to the invariant structure or it *attunes* to it" (Gibson, 1979, p. 249, original emphasized). Building on this, Riva (2018) proposes an operational account of ecological resonance. He argues that "to explain resonance is to account for the coupling of the dynamic systems at the ecological and intra-organismic scales in terms of the ecological variable that constrains a given agent-environment interaction" (2018, p. 41). In this sense, ecological resonance refers to the infinitesimal coupling: the dynamics of agent-environment interaction are coupled to the agent's central nervous system in terms of the same ecological information, which is revealed at the scale of behavior and specifies the available affordances.

While resonance captures a system's sensitivity to structured information in the environment, *attunement* carries a more intentional connotation (Larré, 2001). Ryan and Gallagher argue that resonance is a more passive concept, whereas attunement

involves a dynamic adjustment. For instance, during music improvisation, the musician "must be attuned and responsive to what has been played and is currently being played, just like someone walking down the street must be attuned and responsive to what is happening to the ground and around them" (Ryan and Gallagher, 2019, p. 11). Attunement thus embodies the sense of connection individuals experience—the qualitative aspect of *self-tuning* to environmental variables. It is the experiential quality of perceiving one's actions, emotions, or thoughts as both influenced by, and exerting influence upon, elements of the surrounding world (Charalamboni and Djebbara, 2021, p. 7; Vaz Sánchez, 2021, p. 81). As Vaz Sánchez (2021) notes, one may perceive one's movements as attuned to a song or to the rhythms of a city while walking, even in the absence of measurable entrainment. Nonetheless, the experience of attunement is closely linked to dynamic coupling processes and is, in many cases, the experiential outcome of some degree of entrainment (Charalamboni and Djebbara, 2021).

Entrainment operates at multiple levels—physiological, behavioral, and social—and generally refers to the temporal alignment of oscillatory activity with an external rhythm. Laksis, Givón, and Thun define entrainment more precisely as "the alignment of one or more oscillating systems to an external rhythm, whereby the interactions are multidirectional, that is, the external rhythm influences the oscillating systems but not vice versa" (2018, p. 990). This multidirectional aspect of entrainment is a key feature distinguishing entrainment from ecological resonance.

2.1 Empirical evidence on agent-environment couplings

Evidence of neural entrainment highlights the significant role of environmental features (Djebbara et al., 2021; Charalamboni and Djebbara, 2020) in shaping these complex interactions. For example, research on neural entrainment has demonstrated phase-locked synchronization of neural oscillations in the visual cortex at an alpha frequency to the rhythmic frequency of an external flickering light. This synchronization often results in periodic fluctuations in visual perception, causing moments where vision appears sharper (Mellor et al., 2012; Squid et al., 2014). Attention may also rhythmically modulate perception, producing cycles of heightened and reduced perceptual sensitivity (Papadopoulos et al., 2012; VanVleet, 2016; VanVleet, 2019). Sensing the world is, thus, an active process that leverages temporal regularities to anticipate future events across sensory modalities. A clear example of this cross-modal temporal anticipation is speech perception. During conversation, the visual input of a speaker's lip movements provides crucial temporal cues for upcoming auditory inputs (Schmid et al., 2009), facilitating speech comprehension. Interestingly, entrainment can occur in response to quasi-rhythmic patterns characterized by a successive build-up and release of tension, where each release prepares for the subsequent escalation.

These mechanisms indicate how perception is an active, temporally structured process that adapts to environmental rhythms. They highlight two central processes associated with theories of direct perception: active sensing (e.g., sniffing, eye

movement, and saccades or micro saccades) and dynamic attending (Large and Jones, 1999; Lakatos et al., 2019). These processes involve actively detecting and then enhancing the sensing of behaviorally relevant environmental information (while suppressing irrelevant aspects), as well as preparing the system for forthcoming input flows through the generation of rhythmic expectations (Ocklenburger et al., 2010; Vanhulstijn, 2011). The idea of active sensing is fundamental to the concept of direct perception and the notion of resonance in ecological psychology. Gibson notes that "[t]he state of a perceptual system is altered when it is attuned to information of a certain sort. The system has become sensitized. Differences are noticed that were previously not noticed. Features become distinctive that were formerly vague" (Gibson, 1979, p. 249). Active detection of behaviorally relevant environmental information is facilitated by dynamic periodicities in visuospatial attention¹, which are shaped both by extrinsic structural properties and by intrinsic factors such as intention, motivation, and affect (Galland and Ben Hamoud, 2022).

Embodied engagement with architectural and spatial rhythms, perceived dynamically through movement, can scaffold experiences of attunement between an agent and their surroundings, reinforcing the view that perception is an active, temporally structured process. The inherent temporal regularities in the environment help predict and anticipate upcoming sensory events, thus optimizing behavioral performance (Cavan et al., 2013; Späak et al., 2014). Moreover, the perception of such structures is not only modulated by movement but can also receptively constrain movement, as demonstrated in cases of sensorimotor coupling (Djibbuna et al., 2019; Djibbuna et al., 2021). This suggests the possibility of natural attunement (see Charalambous and Djibbuna, 2022) with continuous environmental stimulation, such as, for example, the rate of change of visual features in the optic flow. For instance, Leonards et al. (2016) demonstrated that the directional pattern of the flow tilt can subtly alter walking trajectories, causing individuals to veer from a straight path. Similarly, Ludwig and colleagues (2018) found that the perceived rate of change of vertical stripe patterns influenced walking speed: when the space between stripes was reduced—creating the visual impression of rapid motion—participants walked more slowly. A real-world application of this phenomenon can be seen in traffic safety interventions. Thaler and Hansen (2021) reported that decreasing the spacing between white road stripes along Lake Michigan's east coast led to a reduction in driving speed, demonstrating how environmental rhythms and affordances can be intentionally designed to guide behavior.

2.2 Becoming attuned to extra-individual relational structures

These behavioral effects suggest that environmental (built) structures may engender a sense of attunement through

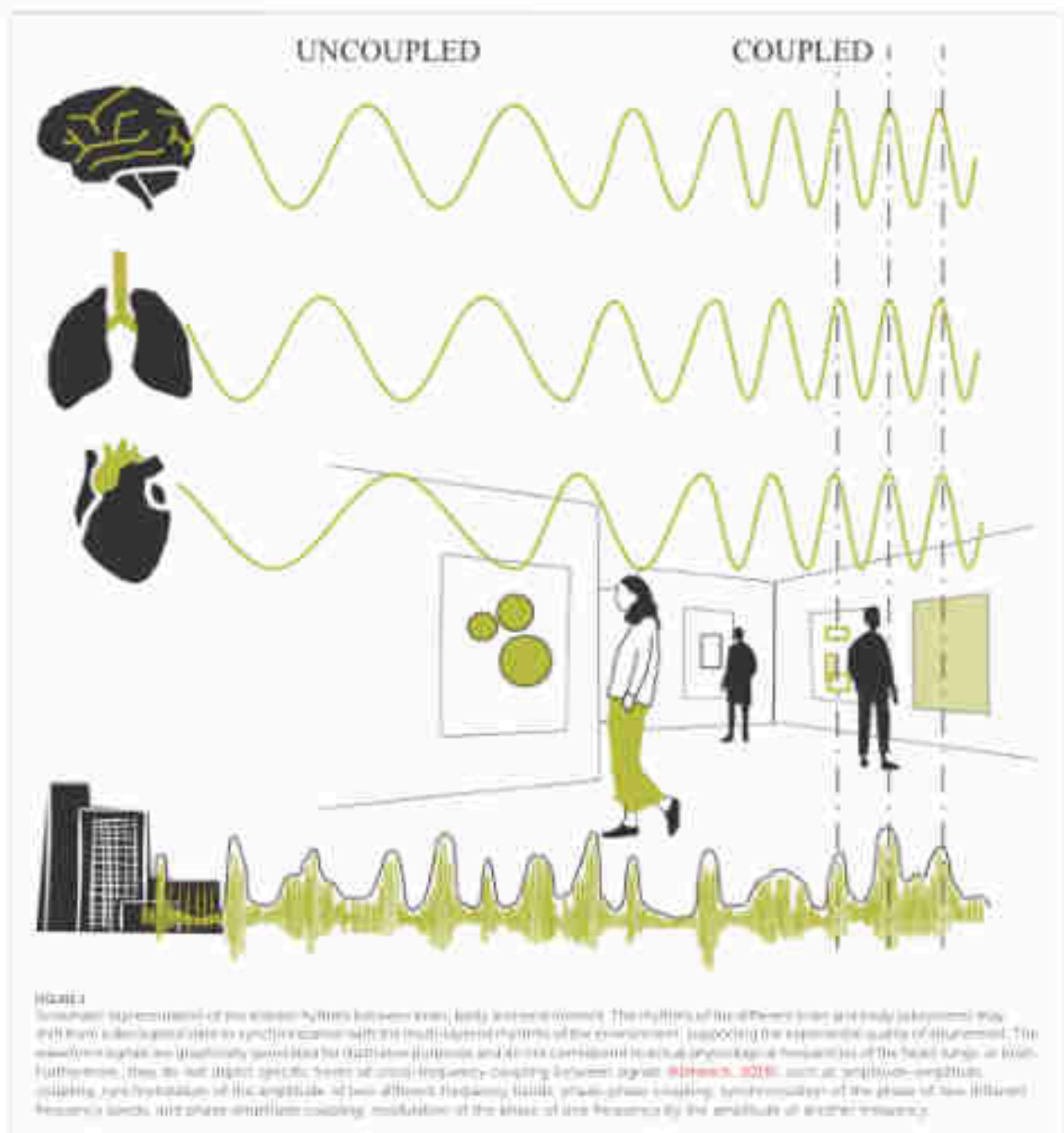
movement and spatial interaction. For example, the behavior setting and atmosphere of a museum, as illustrated in Figure 1, can be conceptualized as a 'bundle of different rhythms', of fluctuations of environmental information, modulating coupling processes between body-brain rhythms and the sociomaterial environment. Perceptual systems—comprising the sensory organs, the motor system, the nervous system, and their coordinated activity—can couple with the perceptual information contained in environmental energy flows, such as light or vibrating air. Such information specifies the available affordances, and the agent's responsiveness to the relevant affordances is closely linked to the behavior level of analysis (Rau and Si Wn, 2013).

Phenomenological perspectives² informed by ecological psychology and enactivism suggest that the detection of relevant affordances gives rise to an embodied readiness for action—a pre-reflective phenomenon felt corporeally, which links the phenomenological to the behavioral scale of analysis (Bruneberg and Rietveld, 2014; Rietveld and Kiverstein, 2014; Rietveld et al., 2018). As Rietveld, Denys and Van Westen claim, "the experienced invitation of an affordance [...] can be measured (and analyzed) as a state of 'action readiness' in emotion psychology and (affective) neuroscience" (2018, p. 3). These states of action readiness "originate in fluctuations of affect" that orient individuals towards affordances that matter to them (Kiverstein et al., 2019, p. 2858).

Behavior settings such as museums, restaurants or contemplative places exhibit stability over longer periods, forming patterns of action readiness associated with the slower dynamics of sociomaterial practices. These patterns of action readiness "can ensue or constrain faster affordance-related states of action readiness" (Rietveld et al., 2018, p. 22), thereby pre-structuring which states of readiness are likely to be adopted. To accommodate what the individual cares about in the particular situation—shaped by personal dispositions and the atmosphere of the setting—multiple affordance-related states of readiness interact and self-organize to generate coordinated engagement with the world (Vrinda et al., 2014; Rietveld et al., 2018). For example, the behavior setting of a contemplative place may invite general patterns of readiness for quiet, slow actions (e.g., speaking softly), but distinct affective dispositions differentially respond and the experience of attunement with the atmosphere of the place: tourists are more likely to explore and observe the architecture and ornamentation of a temple, while devotees may remain seated in quiet contemplation and prayer. As Rietveld, Denys, Van Westen remark: "[s]tates of action readiness characterize affective states in ways that reflect the strings of organisms to modify its relation to the environment [...] Relevant affordances move us, affect and select us as they get us ready to act [...] Affective (sensory and action) readiness are two sides of the same coin" (2018, p. 14).

¹ It involves continuous attentional sensory modulation during the movement. An relevant stimulation was modulation focusing on specific elements with behavioral significance or perceptual salience (Galland and Ben Hamoud, 2022).

² We refer here to the Dutch phenomenology framework developed by ecological psychology by Rietveld and colleagues (Rietveld and Kiverstein, 2014; Van Dijk and Rietveld, 2018; Rietveld et al., 2018).



3 Different perspectives associated with situated affectivity

Gelberis and Scarantino (2005) conceptualized emotions as *forms of skilful engagement with the world*, emphasizing their environmental embeddedness and shaping the notion of *situated affectivity*. Building on this, several related concepts, including *affective affordances* (Krueger and Colombetti, 2018), *affective arrangements* (Slone et al., 2019) and *affective scaffolding* (Colombetti and Krueger, 2015; Colombetti et al., 2018), have emerged, deepening our understanding of *situated affectivity*. Furthermore, they contribute to the study of *atmospheres*, which

has sparked interdisciplinary discussions across cultural studies, phenomenology, and architectural theory (e.g., Andrusson, 2009; Schaefer et al., 2011; Gelberis, 2016; Canepa et al., 2019; Massumi, 2001a; Dybbroe, 2023; Verbeke and Nijssen, 2025).

The concept of *affective affordances* refers to the perception of environmental features “as affording regulative opportunities to amplify, suppress, extend, enrich, and explore the phenomenal and temporal character of our affective experiences” (Krueger and Colombetti, 2018, p. 214). A straightforward example is the affective transmutation induced by different sensory qualities of natural light and darkness. However, the ability to detect and resonate with affective affordances is significantly shaped by an

agent's habits, affective state and history of interactions with elements of their environment. Furthermore, the configuration between the different environmental elements plays a crucial role in regulating affective experience.

The idea that human affectivity is shaped and supported by external structures and environmental resources in a much broader sense, including things, spaces, activities, and other people, is linked to the notion of affective scaffolding (Columbetti and Krueger, 2019; Krueger and Columbetti, 2018). The term describes how the physical and social environment provides *mediating structures* that enable cognitive and affective processes to extend beyond the organism (Columbetti, 2017). In this sense, sense-making and affectivity are not confined to internal states but are dynamically co-regulated by external resources. The ability to regulate affective states by actively modifying one's environment is linked to the concept of niche construction, which Gibson (1977/1986, p. 128) defines as referring "more to *how* an animal lives than to *where* it lives. The niche implies a kind of animal, and the animal implies a kind of niche". In this view, affective niche construction involves material elements, practices, social groups, and cultural structures that shape and organize our affective life.

The heterogeneous ensembles encompassing "persons, things, artifacts, spaces, discourses, behaviors, and expressions in a characteristic mode of composition and dynamic relatedness" are what Gabry et al. (2019) refer to as *affective arrangements*. This term captures the affective interconnectedness within a given sociomaterial setting, including the affective interactions between an agent and elements of their environment. Much like behavior settings, which emerge through coordinated actions, affective arrangements (found at workplaces, sports stadiums, and ceremonies) bring multiple agents "into social alignment with one another" (Krueger, 2021), structuring their orientation within a material context – what to do, how, and when. This results in what Gabry et al. (2019, p. 5) described as "a dynamic, orchestrated conjunction", where affective experience is shaped through collective participation in a shared environment.

Affective arrangements encompass broad affective dynamics, similar to the holistic and affective qualities of atmospheres. However, Gabry et al. (2019) observe that this dynamic quality of locally arranged affect can only be adequately described in specific situations in terms of atmospheres.⁵ Conversely, Krueger (2021) employs the concept of affective arrangements as a tool to analyze how atmospheres animate and regulate actions at both individual and collective levels. For Krueger, affective arrangements are types of atmospheres: they carry an overall unifying feel or affective tonality, and they actively shape the possibilities for emotional experience, behavior, and social connection that may be present or absent in particular locales. Approaching atmospheres through the lens of

affective arrangements emphasizes their capacity to influence dynamics of belonging—how they support different bodies in finding a sense of connection with the part of the world defined by these arrangements, and how they scaffold the development of "different habits, practices, and forms of self-experience" (Krueger, 2021). Furthermore, the concept of affective scaffolding, including Krueger and Columbetti's (2018) notion of affective affordances (i.e., how environmental features invite actions related to emotion regulation), suggests that atmospheres can be understood as part of our scaffolding practices oriented toward the affective dimensions of daily life. According to Columbetti and Krueger (2015), atmospheres can also be seen as part of the affective niches that we construct to regulate affective experience by modulating the affective salience of specific networks of affordances.

Phenomenological accounts on affective atmospheres suggest that they exist as a spatial-like state of the world and as an affective tonality resonating in the peripersonal space of the feeling body, that is, an experience "felt in the region of," but not identical to one's body (Schmitz et al., 2011, p. 245; Geilert, 2014b). While affect is concerned with "a body's relation to the world or a relating of two evolving bodies to each other", – atmospheres, as relational and dynamic phenomena, extend beyond the individuals. They encompass the "meshwork of all bodies (and worlds) in a shared situation" (Rudel, 2019, p. 269), showing how affective experience is not only embodied but also spatially and socially distributed. Ben Anderson notes that affective atmospheres are a class of experience that lies in-between subject/object distinctions, arguing that as collective affects they provide a "shared ground from which subjective states and their attendant feelings and emotions emerge" (2009, p. 78) in ways that modulate how we inhabit specific situations, that, the relationship between affectivity and atmosphere cannot be reduced to the mere experience of a potential feeling.

From an ecological-enactive perspective, affective atmospheres shape embodied, pre-reflective responsiveness to relevant affordances that invite action (Garcia, 2024; Velasco and Nakawa, 2022). Garcia (2014) argues that they stable a shift from the background of the *landscape of affordances* (Gibson and Krukowski, 2014; Van Dijk and Rothfeld, 2016) – all potential actions available to a given form of life⁶ – toward the lived experience of the *field of affordances*, that is, the specific possibilities for action in which an individual is responsive in a given situation. By affectively tuning the situation, affective atmospheres make certain affordances stand out as more salient than others. From this perspective, atmospheres can be understood as high-level, nested relations of agent-environment joint potentialities, which are grasped corporeally and affectively (Velasco and Nakawa, 2025).

4 Emerging themes

The scholarship on situated affectivity and atmospheres, together with empirical and theoretical work on dynamic agent-environment interactions, foregrounds the relational structures (e.g., affordances, behavior settings) that shape out

⁵ The essence of this passage—regarding the issue of the term "atmosphere"—is not usually attended. It may stem from the observation that the social set-ups of affective arrangements, such as temporary arrangements or corporate offices, can establish affective relations that extend beyond the specific location of the arrangement and ensuing focus, by means of "affective connectivity" (Gabry et al., 2020).

⁶ The term is used by Velasco and Nakawa (2022) to capture the variety of practices within the human way of life.

attunement to environmental features, individually and collectively. Building on the preceding discussions of resonance, attunement, entrainment, and affective relationality, this section synthesizes insights from current scholarship to highlight how cognition is both relational and temporally structured through brain-body-environment couplings. It emphasizes the need to move beyond static accounts of architecture and reconsiders the temporal unfolding of architectural experience, an often-overlooked dimension in (neuro)architectural research and design. In doing so, the section introduces conceptual vocabularies that capture change over time and considers how such approaches can inform inclusive practices, particularly in relation to (neuro)diversity. The themes that emerge from approaching situated affectivity through the perspective of a moving, intentional body rather than a fixed observer point toward new directions for future research and design.

4.1 A process-oriented and relational approach to situated affectivity

Various situated perspectives of affectivity emphasize a primordial affective registering of relations (Colombetti, 2014, 2017), understood as a concrete, direct perceptual grasp similar to affordances. For example, affective arrangements can be seen as “prepared occasions for affective engagement, for absorption and attunement” (Slaby, 2018, p. 273). Similarly, atmospheres have been described as “ecological tones or meanings” (Gibson, 2014b, p. 46), environment-agent joint potentialities (Velasco and Nakawa, 2022) and fields of potential where specific actions “bubble up”, becoming more salient, conditioned, or induced (Massumi, 2021a). Atmospheres, thus, modulate “the whole landscape of affordances and the felt body that resonates with it, settling the background from where concrete and relevant affordances may emerge” (García, 2024, p. 17).

This relational and process-oriented dimension of affectivity is also highlighted in Massumi's (2021a) approach to atmospheres. He describes them as collections of events, “involvements of particles, bodies, and rays, billows of winds and shifts and shafts of light, reflections and sounds, echoes and contrasts, overshadowing, all coming together in a singular feeling.” Notably, he notes that this is not merely a simple aggregate but “a coming-together in reciprocal activity” (Massumi, 2021a, p. 204). A closer look at resonance, through the example of an echo, reveals the two-way movement inherent in atmospheric feeling. As Massumi (2021b) explains, “[resonance] fills the emptiness with its complex patterning... The bouncing back and forth multiplies the sound's movement without cutting it.

This complex self-continuity is a putting into relation of the movement to itself: self-relation.” He argues that the best term for this “complicating immediacy of self-relation is [Massumi (2021b) pp. 13–14]. These intensities generate a particular affect within the individual, where the atmospheric feeling of the affective tone coincides with the transmission of a dynamic form, a pattern of activity” (Massumi, 2021b, pp. 194–196).

Taken together, these accounts of atmospheres, resonance, and intensity foreground affectivity as a dynamic, processual phenomenon rather than a static property of environments or individuals. The conceptualization of atmospheres as a collection

of events that come together in reciprocal activity and as a field of joint potentialities between the individual and the environment serves as a stepping stone towards understanding affect as a process. Extending current critiques that challenge traditional static view of architectural experience (Robinson, 2021d), this perspective of affectivity draws attention to its temporal unfolding, opening pathways toward a more process-oriented understanding of the affective experience of architectural space.

4.2 Exploring affectivity through the orchestration of brain-body-environment rhythms

The dynamic embodied experience of being affectively “gripped” by an atmosphere is, according to Slaby (2014), a form of “phenomenal coupling” with structures or processes in one's environment that itself has dynamic phenomenal characteristics. This interaction between environmental dynamics and the active feeling body becomes manifest as “an arena of significant opportunities” for embodied engagement with the world. It is experience as “felt bodily potentialities” through which the environment is apprehended (Slaby, 2014). Interoceptive sensations shaped by prior experience and the visceral body rhythms of organs, muscles, and joints inform our ongoing engagement with the world. These bodily-affective changes are integrated with current exteroceptive multisensory information to improve the estimation of expected uncertainty through a future-oriented anticipatory mechanism (Gallagher and Allen, 2018).

The metaphor of the felt body as “a sounding board for spatially ‘poured out’ atmospheres” (Slaby, 2018, p. 278) suggests a process of bodily resonance between internal and external rhythms. According to Vera Sánchez, the idea of bodily resonance is often associated with the phenomenological notion of the feeling body rather than the physical body, highlighting a relatively passive view of the body. Building on empirical evidence on how visceral shape brain dynamics and cognition (see Asakura et al., 2019), Vera Sánchez argues that “role of the body in the embodiment of emotions, thus, is not only sending interoceptive information to the brain [...] or bodily resonance, it plays, as well, an active part on the rhythm that enacts along brain oscillations” (Vera Sánchez, 2019, p. 725). Rhythm, beyond mere repetition, can be conceptualized more broadly as flow or form (Kernaghan, 1951, p. 287)⁵ or as “an evolving pattern of oscillations able to entrain other oscillations” (Vera Sánchez, 2020, p. 88). Such enactive and dynamic views of affectivity (Colombetti, 2014; Vera Sánchez, 2019) highlight the

⁵ Kernaghan offers a historical reconstruction of the term rhythm, defining it as a “distinct narrative character” arranged in a series with a climax. This concept implies a non-linear structure that is not fixed, subject to change “in arbitrary succession or something flowing.” While the metaphor of sound strongly informs Kernaghan's view, he also acknowledges that “each particular configuration of movement or flow are related to an individual.”

importance of focusing on the enacted rhythms and the rhythmic interactions between the body-brain-environment system.

There are different qualities of rhythm we can experience in the built environment, often linked to a tension between oppositions (Vatn-Sandnes, 2021). Various rhythmic phenomena—marked by alternations between difference/repetition, tension/release, expected/unexpected, and movement/stillness—shape the overall atmospheric rhythm to which individuals can become attuned. They create environmental structures with temporal regularities that perceptual systems can flexibly use, even across sensory modalities, to support attunement and the anticipation of upcoming events.

Actively engaging with the affective dynamics of environmental structures or processes that manifest expressive qualities (Nahy, 2014)—such as theatrical performance, music concerts, or affective atmospheres (e.g., a crowd of protestors chanting rhythmically)—can modulate bodily rhythms. Recent studies measuring physiological signals (cardiac and respiratory activity, skin conductance responses) in audiences at classical music concerts provide evidence of synchronization across individuals (Tschacher et al., 2020; Tschacher et al., 2024a). The findings suggest that synchronized embodied experiences were linked not only to personality traits but also to the emotional and aesthetic quality of the experience. Moreover, participants' "listening mode" had a measurable impact on synchrony: listeners who reported being attuned to the auditory vibrations of music—including its structure, melodies, rhythms, and instrumental timbres—showed greater synchronization compared to those who reported being distracted or listening only "with half an ear" (Tschacher et al., 2024b). Haptic vibration can also increase the intensity of emotional experiences, heightening, for instance, the sensation of fear when watching a horror movie (Makrakis et al., 2022).

In summary, these accounts highlight how bodily rhythms (which can modulate brain rhythms) interweave with environmental structures to generate dynamic fields of attunement. Evidence of collective synchronization in musical and performative contexts further illustrates how atmospheric rhythms extend beyond the individual, shaping shared affective experiences that unfold over time. Rhythms also play a key role in architecturally arranged situations, where they function as mediating structures that underpin sense-making and affectivity through agent-environment couplings. Architectural form itself can act as a patterning force that modulates rhythms (Rohmann, 2022b, p. 1), shaping how affective experience unfolds. Current work on situated affectivity suggests that the notion of "affective arrangement" provides a valuable tool for examining this relationality, enabling researchers to trace how local constellations of elements dynamically interact and contribute over time to complex, polystranded formations. This perspective highlights rhythm as a central aspect of situated affectivity, revealing how temporal regularities and oscillatory patterns organize embodied engagement with the world.

4.3 Conceptual vocabularies that capture changes over time

Conceptual vocabularies that capture changes over time such as rhythms, vibrations, and tonality can help explain how different local constellations of elements and energy patterns influence the overall affective atmosphere and the individual's experience within it. *Vibration* and *tone* are two relevant phenomenological concepts

capturing how we attune to environmental features (Ash and Gallacher, 2015). For example, the vibrations associated with urban tactile paving encourage visually impaired individuals to attune to auditory-haptic rhythms, guiding their movement through the city. *Vibration*, as defined by Ash and Gallacher (2015), is a "unit of sense crossing human and non-human boundaries" and can be approached both qualitatively (as felt experiences of intensity) and quantitatively (in terms of frequency, amplitude, phase, damping, and periodicity). Conversely, *tone* refers to how vibrations are organized with specific sensory effects to mind, shaping different tendencies and degrees of attunement.

Furthermore, the concept of vibration shifts the focus to environmental elements that function as thresholds, influencing an object's or body's capacity to act (Ash and Gallacher, 2015). A striking example is the Urban Carpet installation in Aarhus, which explores the relationship between affordances and atmosphere. This installation, as illustrated in Figure 2, is a woven textile of charred wood placed at a crossroad, which draws attention to the unexpected sensory experiences of touch and smell. Altering the texture and olfactory qualities of the space changes pedestrians' walking pace, stimulating spontaneous actions such as foot tapping and dancing (Chelmarova and Rask, 2018). This installation has been discussed in relation to the effects of the perceived resistance and the associated haptic feeling (Rehmisch, 2023a) as well as in terms of its contribution to placemaking as a result of the experience of its sensual effects (Christiansen, 2020).

Moving towards a more process-oriented perspective we focus here on the shift of the multisensory experience and how it relates to the phenomenon of *sustainable attunement*, a term from dynamic systems theory that captures the flexible balance between stability and openness to modify in agent-environment coupling (Brenneberg et al., 2021). Metastable attunement refers to the ability to maintain a dynamic, responsive state that enables flexible switching between different modes of skillful engagement with the environment such as switching from exploiting already familiar action possibilities to experimenting with novel ones in response to situational demands (Brenneberg et al., 2021). By becoming attuned to environmental dynamics, the body-brain system helps anticipate and prioritize actions that will minimize uncertainty. From an ecological-enactive perspective, this active inference⁶ is associated with the tendency towards an optimal

⁶ This is an alternative interpretation of Friston's theory of the minimizing brain (Friston, 2022). It offers a perspective of how energy minimization (reduction of uncertainty or prediction error) as a tendency to reduce the degree of disalignment between internal dynamics and environmental dynamics by rapidly accommodating novel conditions from the responsive conclusion through skillful engagement with the environment (Brenneberg et al., 2020). The practice of active inference (providing predictive engagement) highlights active inference as being less a matter of inferring that inference "involves an active adjustment, a worldly engagement—with anticipatory and corrective aspects already involved" in which "the brain, as part of and going with the world, organizes, actively responds in ways that allow for the right kind of ongoing adjustment with the environment's own environment that is physical but also social and cultural" (Gallagher and Niek, 2018, p. 2024).



Figure 2
Urban Carpet installed by [Polina Christakopoulou](#) in collaboration with [Uwe Simon Christakopoulou](#), [Astrid Christakopoulou](#), [Polina Christakopoulou](#), [Katharina Christakopoulou](#)

grip on a particular situation, or more precisely, a tendency towards an optimal metastable attunement in the dynamics of the environment ([Brunnberg and Rietveld, 2014](#); [Brunnberg et al., 2018](#)). This reflects a readiness to switch between behavioral patterns in response to environmental demands and the individual's needs. The function of the Urban Carpet as a threshold illustrates well how metastable attunement enables context-sensitive, selective openness towards anticipating new forms of interaction with the environment, such as foot tapping and dancing. The subtle variations in vibration that arise when walking on the charred wood invite different states of action-readiness, which generate new action tendencies and facilitate a switch into new behavioral patterns.

In addition to the Urban Carpet example, the *Reversible Dystopian Loft* of [Arakawa and Gins](#), as illustrated in [Figure 3](#), offer a complementary architectural case potentially associated with metastable attunement. The design of these lofts is strongly linked to their concept of "architectural body" as a relational field ([Gins and Arakawa, 2002](#)) between the proper body of the organism and environment—constantly being recalibrated through sensory engagement. In particular, by introducing cliffs in the sensory experience through chromatic contrast, textures, uneven floors and slopes they destabilize habitual ways of engaging with a domestic environment, compelling inhabitants to actively re-attune and change their behavioral patterns and actions. As argued by [Brunnberg et al. \(2021\)](#) this sensitivity to novel situations and the sensitivity to a multiplicity of action possibilities is linked to the property of metastable attunement.

Anticipating an affordance within a specific context generates an action readiness pattern. As [Brunnberg and Rietveld \(2014\)](#) note, this makes the affordance stand out as relevant. The relevance of

locally available affordances is felt corporeally in the skilled body as states of affordance-related action readiness that are simultaneously affective and behavioral ([Kerstetter et al., 2019](#)). Considering the different dynamics and relational structures that emerge between the brain, body and the architecturally arranged surroundings offers a promising approach that can advance design practice. Conceptual vocabularies, such as rhythms and vibrations, "capture" the energy patterns in the built environment including fluctuations in sound, light, and temperature that vary over time or in response to movement and play a key role in rethinking the temporal dimension of architectural experience.

4.4 Advancing research and design for (neuro) diversity

The agent's selective openness to the available affordances depends on dynamical patterns that unfold across multiple timescales. Slower-evolving dynamics, such as sociocultural practices, constrain the faster-evolving dynamics that shape the process of attunement to the current context ([Brunnberg and Rietveld, 2014](#); [Velasco, 2023](#)). Consequently, abilities acquired through a history of engagement in sociocultural practices ([Rietveld, 2009](#)) shape how an individual perceives, responds to, and attunes to the actions that a particular situation affords. Differences in prior experience, bodily skills, personal tendencies, affective dispositions and broader social, cultural and gender dynamics influence responsiveness to higher-order networks of affordances while atmospheres (similar to behavior settings) "shape the potentiality of what is to be felt, perceived or acted on" ([Garcia, 2024](#), p. 18). These differences may cause specific individuals to feel disoriented or excluded in particular



Figure 1. Masayuki Arai, Resonance Design Loft—Hiroka (in Memory of Hiroki Arai), 2019. New residential apartments (low-cost type), central area. © 2022 by A. Chiriac-Bouché. Hiroka, Japan. Photo by: Masayuki Arai. © 2020 Resonance Design Foundation. Reproduced with permission of Resonance Design Foundation.

environments. Krueger (2021) argues that an inability to tune into the affective arrangement of a setting may create a form of affective dissonance at a pre-reflective level, similar to the discomfort caused by spatial disorientation (Charalambous, 2019; Charalambous et al., 2021). This suggests that some atmospheres, for example, might be more inclusive than others in promoting social interconnectedness and shared experiences. For example, a neurodivergent individual may experience difficulties tuning in and orienting in environments that are noisy or brightly lit. In contrast, adjustable lighting or variability in lighting conditions in public spaces may reduce the possibility of sensory overload and emotional distress. Designing for (neuro)diversity requires recognizing how specific settings may not be adequately configured to accommodate different styles of “bodily being-in-the-world”, thereby limiting possibilities for social connection, attunement and the feeling of “being at home” (Krueger, 2021, p. 127).

The feeling of “being at home” is scaffolded synchronically by the immediate material and sensory context one engages with and diachronically by the social, cultural, and material practices that shape one’s lived experiences. Through these practices, individuals develop confidence in their relationship with the environment and an “affective trust” in the reliability of specific environmental resources serving as affective scaffolding (Krueger and Columbetti, 2018). This trust contributes to a more general attitude of certainty or “basic trust” in the surrounding world, supporting unreflective, habitual actions (Habets et al., 2024).

However, when this fundamental trust is disrupted (due to persistent stress, cultural displacement or psychopathological conditions), it can result in a diminished sense of bodily resonance with the world, ultimately restricting access to affective

regulation (Krueger and Columbetti, 2018; Habets et al., 2024). Given this, it is crucial to conceptualize urban environments as constellations of affective niches, of public places (e.g., streets, canals, rivers, seaside areas, squares, parks, and contemplative places) as feeling hubs offering affective affordances that support emotional regulation and well-being.

5 Conclusion

The dynamic approach to cognition offers conceptual tools that can advance both empirical research on agent-environment relations and architectural design research. Rhythm emerges as a central unit of analysis within these lines of inquiry, linking brain, body, and environment. Bringing into dialogue non-representational notions such as resonance, entrainment, attunement, affectivity, and atmospheres enables deeper exploration of shared rhythms and natural attunement (Charalambous and Djelkhara, 2021) as integral aspects of affective experience at the individual and collective level. Complementing arguments that emphasize the temporal dimension of architecture (e.g., Robinson, 2023), this conceptual synthesis highlights the need for a relational and process-oriented perspective, challenging static stimulus-response models.

Conceptual vocabularies that capture change over time, such as rhythm, vibration, and totality, provide valuable tools for design, enabling the study of the affective dimension of architectural experience and how it unfolds dynamically over time. They also support the development of research on dynamic phenomena such as mutable attunement, in which transient disequilibrium in agent-environment coupling is experienced as affective tension and resolved by engaging with relevant affordances (Reinberg and Riepschold, 2010). Crucially, the selective openness to the available

affordances and the related action-readiness patterns are shaped by experiential priors, which are inherently linked to individual, social and cultural dynamics. Therefore, future research on the relationship between the built environment and situated affectivity should take into account such differences that influence the experiential quality of attunement between internal dynamics and environmental rhythms. Examples of this line of inquiry include exploring how different individual, social and cultural factors shape differential attunement to affective affordances and atmospheres in architectural environments or how gender differences influence attunement to urban rhythms. Attention to diversity across gender, culture, and social contexts can not only advance scientific knowledge but also inform the design of more inclusive spaces that embrace diversity. By foregrounding temporality and rhythmic interaction, the emerging themes call for new methodological approaches capable of capturing the situated, embodied, and affective mind in its *ongoing* engagement with the dynamics of the physical, social and cultural environments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

EC: Conceptualization, Writing – original draft, GS: Writing – review and editing, TCB: Writing – review and editing.

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The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Anderson, B. (1999). Affective atmospheres. *Emot. Space Soc.* 2 (2), 77–91. doi:10.1016/S1469-858X(99)00040-0
- Ali, S., and Galichet, L. (2015). Boosting attitudes, shared affects and embodied intelligence. *Maths4all: Embodied Learning Based QoL Res.* 69–75. doi:10.3204/9783310211961_6
- Arnold, D., Kubie, J., and Tsalikis, C. (2019). Visual inputs shape brain dynamics and cognition. *Trends Cognitive Sciences* 23 (6), 489–505. doi:10.1016/j.tics.2019.05.007
- Baker, R. G. (1998). *Biological psychology: concepts and methods for studying the environment of human behavior*. Stanford, CA: Stanford University Press.
- Barnes, J. (1991). The concept of rhythm in linguistic expression. *J. Psycholinguistic Theory* 14 (1), 411–419.
- Bauer, M. J., and Epstein, R. A. (2017). Coding of negotiated affordances in the human visual system. *Proc. Natl. Acad. Sci. U. S. A.* 114 (18), 4795–4798. doi:10.1073/pnas.1612201114
- Bruinsma, J., and Barwell, E. (2014). Self-regulation, free-energy minimization, and optimal grip on a field of affordances. *Front. Human Neuroscience* 8, 946. doi:10.3389/fnhum.2014.00946
- Bruinsma, J., Kivimäki, J., and Barwell, E. (2016). The anticipatory brain is not a vacuum: the free energy principle from an ecological reaction perspective. *Front. Hum. Neurosci.* 10, 2447. doi:10.3389/fnhum.2016.002447
- Bruinsma, J., Schödl, L., Rens, M. J., and Kivimäki, J. (2023). Neurophysiological and real-life skilled behavior. *Psychol. Rev.* 130 (1), 12915–12947. doi:10.1037/a0036021
- Buzsáki, G. (2020). Time, space, memory, and brain-body rhythms. *Nat. reviews Neurosci.* 21, 61–78. doi:10.1038/s41562-020-0848-2
- Cinque, R., Scarla, V., Fazio, A., Accornero, L., Lagravese, G., and Chiarri, C. (2010). "Affordances: linking architecture to cognition." *Architecture*, 100. doi:10.1000/archives.2010
- Charalambous, E. (2019). *The affect experience of spatial representation*. London, United Kingdom: University College London PhD Thesis.

- Columberti, E., and DeBorja, Z. (2022). Sati without attention: shared rhythms between the brain and the environment. *Sensory Mathematical Reviews* 175, 103836. doi: 10.1016/j.smr.2022.103836
- Columberti, E., Harris, E., and Patten, A. (2021). What I know when I am: the contribution of perceptual cues to orientation in urban environments. *Spatial Cognitive Computation* 20 (3), 307–334. doi: 10.1080/10897502.2021.1960458
- Columberti, E., and Raitt, K. (2018). Mediating new industrial-environment relations through repositioning in affluence. *Architecture (Penguin)* 4 (4). doi: 10.4000/architectures.1448
- Cramer, J. (1997). An outline of a theory of affordances. *Evol Psychology & Publications for Soc-Evol Psychol* 13 (2), 181–190. doi: 10.1023/a:1022322222222
- Crimmins, T. M. (2001). Technology and the city. Aarhus, Denmark: Aarhus University Press. doi: 10.7557/85.2123.TfC14.D0008
- Columberti, G. (2014). The feeling body: affective sensor maps for creative social MIT press.
- Columberti, G. (2017). Emotive-affective, embodied space. *Archit Res Philosophy* 36 (1), 247–272. doi: 10.1080/03113325.2016.1155552
- Columberti, G., and Krutiger, J. (2019). Scalability of the affluence model. *Physica Psychologia* 28 (6), 1157–1176. doi: 10.1080/09507690.2019.1650318
- Columberti, G., Krutiger, J., and Roberts, Y. (2018). Embodied affectivity beyond the map. *Front Psychology* 9, 1807. doi: 10.3389/fpsyg.2018.01807
- Cumy, A. M., Kolchinskii, U., Wynn, Y., and Naim, A. V. (2018). Temporal expectation influences contrast sensitivity by phase entrainment of low-frequency oscillations in visual cortex. *J Neurophysiol: The Official Journal of the American Physiological Society* 119, 4893–4910. doi: 10.1152/JN.00662.2017.12.2013
- Cusack, R., Schwartz, B., and Katz, J. A. (2012). Cognition through the lens of a body-brain dynamic system. *Trends Neuroscience* 35 (9), 467–477. doi: 10.1016/j.tics.2012.06.002
- Daffney, Z. (2022). Affordances to consider for a multiscale-affluent ecology of cities. Springer Nature.
- Daffney, Z. (2023). "Methods of the brain, body, and behavior – meet a neuroscientific perspective on atmosphere." In *Designing atmospheric theory and science*. Dordrecht: Editors E. Langer and B. Goetsch (Motivation, Ed.), 75–111.
- Daffney, Z., Fick, L. E., Borra, L., and Guzman, K. (2019). Sensorimotor brain dynamics reflect architectural affordances. *Proc Natl Acad Sci U S A* 116 (24), 14768–14778. doi: 10.1073/pnas.1808048116
- Daffney, Z., Fick, L. E., and Guzman, K. (2021). The brain dynamics of architectural affordances during transition. *Art Systems* 1 (1), 1796. doi: 10.1080/24741940.2021.820416
- Daffney, Z., Jones, O. R., Parula, F. J., and Graham, E. (2021). Neurocognitive and mechanistic modeling balance through sensorimotor responses in the built environment. *Sensors: International Review* 18 (10), 3325. doi: 10.3390/s18103325
- David-Rade, S., and Val, S. (2019). The open-spectrum prosody. *Philosophical Transactions R Soc Lond Ser B Biol Sciences* 374 (2020), 1843–1853. doi: 10.1098/rstb.2019.0183
- Dehaene, S., Spelke, E. S., and Geary, D. (2015). Space and time perception: effects of individual and cultural differences. *Psychological Science* 26 (1), 15–34. doi: 10.1177/0956797614560071
- Ellen, D. A., Nagatani, F. M., Ge, X., and David-Rade, S. (2018). "Embodied temporal perception of music," *Frontiers* 9, 1–8. doi: 10.3389/fnins.2018.01834
- European Union's Horizon (2021). Research and innovation program under the Marie Skłodowska Curie grant agreement no. 101019180. doi: 10.3060/101019180
- Fick, N. H. (2014). "Intention and action," in *Feeling and knowing: the attentional properties*, 159–173.
- Fick, N. H., Radtschke, K. R., and Blomberg, E. (2014). Intuitive action-oriented impulses and their embodiment. *Psychology* 5, 205. doi: 10.1186/psyc.2014.010105
- Foster, E. (2015). The homology principle: a unified brain theory? *Nat Rev Neurosci* 16 (12), 123–138. doi: 10.1038/nrn3787
- Galland, C., and Ben Barak, E. (2022). The neural basis of spatial attention and perceptual rhythm. *Eur Journal Neuroscience* 54 (11–12), 3219–3227. doi: 10.1523/JNEUROSCI.0944-22.2022
- Gallagher, S. (2004). *How the body shapes the mind*. Oxford, England: Clarendon Press.
- Gallagher, S., and Allen, M. (2018). Active inference, embodied cognition and the heterogeneity of social cognition. *Frontiers* 9 (4), 2629–2648. doi: 10.3389/fnins.2018.01269
- Garcia, R. (2014). Affluent atmosphere and the environmental landscape. *Ambio: Psychology* 23 (7), 676–679. doi: 10.1007/s10646-013-2293-0
- Gibson, J. J. (1977). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.
- Givoni, B., and Nakano, S. (2021). Architectural body. Philadelphia, PA: University of Alabama Press.
- Givoni, J., Wolman, A., Hagopian, L., Wolff, A., Anderson, L. A., and Nordhoff, G. (2014). Dynamic mechanisms that couple the body and breathing to the ambient environment. *Environ Biology* 7 (1), 938. doi: 10.1080/2150475X.2014.938425
- Givoni, J., Olson, T., Huber, M. H., Campbell, A., and Ellis, B. (2022). Chronophysiological examination of embodied-in vision and action. *Psychol Science* 33 (2), 152–167. doi: 10.1177/09567976211026078
- Goffman, E. (2014). "Architectural affordances: the atmospheric autonomy of spaces," in *Architecture and atmosphere: design, theory, mechanism, key, foundation*. Editor P. Talbot.
- Goffman, E. (2014). Atmospheric conditions space. *Evol Phenomenologica* 11, 29–51. doi: 10.1007/978-94-007-2514-0_2
- Goffman, E. (2015). *Atmospheric conditions of everyday space*. London and New York: Routledge.
- Goffman, E. S., and Scaramuzza, A. (2015). "Intuition in the wild: the structural perspective on emotion," in *The Cambridge handbook of affective cognition*. Editors P. Scherer and M. Beegle (Cambridge University Press).
- Haley, D., Ratcliff, E., Rayburn, L., and Drury, D. (2024). Translocation (place). *Adapt Behavior* 12 (1), 423–438. doi: 10.1177/1043986223120705
- Hall, D. L., Krutiger, J., and Kay, L. H. (2019). The impact of memory flow on scaling shape memory function. *J Neurophysiology* 122 (3), 945–977. doi: 10.1152/jn.00666.2019
- Hall, D. H., Cornejo, M. L., Yen, M. R., Lu, Y., Alfaro, H., and Vargas, Y. (2022). Brain-mechanisms regulate modulation of brain activity after non-perception on cognitive and emotion. *Biol Psychiatry* 171 (10), 106954. doi: 10.1016/j.biopsych.2022.108954
- Hall, H. (2014). Behavioral settings, situated action, and atmospheric theory. *Philosophical Transactions R Soc Lond Ser B Biol Sciences* 369 (1616), 18216284. doi: 10.1098/rstb.2013.0284
- Hall, H. (2020). The ecological approach to perceiving and the dynamics of environmental influence: a research agenda. *Biol Psychiatry: A Publication for Soc-Evol Psychol* 16 (3), 193–199. doi: 10.1080/10897502.2020.1843434
- Hall, H., Gibson, J., and Barber, K. (2013). *Ecological Psychology in Context: Atmosphere, Design, and the Legacy of William James's Radical Empiricism*. Psychology Press.
- Heckrich, J. M., Davis, M. S., Trötschel, R. C., and Heppner, J. C. (2019). Being at a loss of mental information: selective overestimation via omission. *Psychol Science* 30 (1), 142–147. doi: 10.1177/0956797618800244
- Krout, J., Miller, M., and Keibel, E. (2019). The fading of grip strength, eye dynamics, and the postural brain. *Biotech* 186 (7), 2847–2861. doi: 10.1007/s00122-017-1585-9
- Krutiger, J. (2019). The frequency architecture of brain and body oscillations as analysis. *Eur Journal Neuroscience* 48 (7), 2431–2443. doi: 10.1111/ejn.14042
- Kuo, S. A., Ravignani, S., and Fitch, W. T. (2018). The evolution of rhythmic processing. *Dev Cogn Sci* 12 (1), 399–401. doi: 10.1016/j.dcs.2018.08.001
- Kruppa, J. (2021). "Agency and atmosphere of behavior and malice," in *Atmosphere and shared emotions*. London: Routledge, 113–152.
- Kruppa, J., and Columberti, G. (2019). "Affective affordances and psychopathology," in *Psychosocial perspectives on affective experience and psychopathology* (Qualitative), 221–247.
- Likhtik, E., Olsen, L., and Tran, C. (2019). A new coding scheme of the role of animal movement. *Ecol Biogr* 18 (16), 3280–3285. doi: 10.1016/j.ebi.2019.07.005
- Luigi, L. W., and Jones, M. R. (2019). The distance of standing: how people try to keep waving eyes. *Psychol Science* 30 (1), 134–138. doi: 10.1177/0956797618800244
- Leonardi, G., Fornaci, L. G., Gibo, G., Drake, A., and Radtsch, K. R. (2019). Disordered processes paving the pattern: mostly oriented walking directions. *Adv Sci* 10 (16), 1801004. doi: 10.1002/advs.201801004
- Lofgren, C. H., Alexander, S., Howard, E. J., Ishihara, A. A., Hoffman, L., and Radtsch, K. R. (2018). The influence of visual flow and gestural lead on locomotion speed. *Atmos Perception and Psychophysics* 16 (1), 49–61. doi: 10.1080/15444017.2017.14172
- Makino, T., Okamoto, Y., and Taya, T. (2022). "Difference in skin conductance response to touch and force load sensory input," in *Proceedings of IEEE Global Conference on Atlantic Research*.
- Mancini, B. (2022a). "The, nature, and experience atmosphere in process," in *Cognitive Urban*

- Northoff, G., Eick, P., Jents, M., and Keller, A. (2021). As within, so without: how the brain's intrinsic spatial alignment to the environment shapes consciousness. *Frontiers Neurosci.* 15, 6821076. doi: 10.3389/fnins.2021.6821076
- O'Regan, J. K., and Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral Brain Sciences* 24 (Pt. 2), 883–917. doi: 10.1017/S0140525X01000110
- Papadopoulos, T. C., Georgiou, G. K., and Parric, R. K. (2012). Low-level deficits in fast perception: neither necessary nor sufficient for explaining developmental delays in a common orthography. *Dev. Neuropsychol.* 27 (4), 184–198. doi: 10.1080/17445019.2012.66208
- Rao, V. (2019). A theory of resonance towards an ecological cognitive architecture. *Front. Neurosci.* 13, 28–33. doi: 10.3389/fnins.2019.00028
- Rao, V., and de Wit, M. M. (2022). Attentional switching in self-organizing brain-body-environment systems. *Front. Neurosci.* 16, 897367. doi: 10.3389/fnins.2022.897367
- Riecke, T. (2019). "Affect and atmosphere – two sides of the same coin," in *Affect as atmosphere: 1* (New York: Routledge), 202–225.
- Riecke, T. (2020). Affect and atmosphere: the normative aspect of embodied cognition in atmospheric action. *Mind – A Quarterly Journal of Philosophy* 127 (540), 923–1001. doi: 10.1093/mind/fzab010
- Russell, D., and Crossman, J. (2014). A rich landscape of affordances. *Front. Psychology* 5, 1000000. doi: 10.3389/fpsyg.2014.00000
- Russell, D., Davis, D., and Van Wassen, H. (2014). "Ecological and affective cognition as engaging with a field of relevant affordances: the skilled interdependence framework (SIF)," in *The Oxford handbook of affect cognition*, Editors A. Weiss, J. D. Ryan, and J. Gallagher (Oxford, United Kingdom: Oxford University Press).
- Robinson, S. (2014). *Architecture as verb*. London and New York, United Kingdom and United States: Routledge.
- Robinson, S. (2016). Dampening movement, modulating mood. *Emotions* 1 (2), 97–117. doi: 10.5964/emot.v1i2.4388
- Ross, K. J. B., and Gallagher, S. (2020). Between ecological psychology and enactivism: is there something? *Philos. Psychology* 33, 1147–doi: 10.1080/09513203.2020.181447
- Schmidt, H., Hillier, R. G., and Haby, I. (2011). Emotion outside the box – the neurophysiology of feeling and unpredictability. *Neuroscience & Biobehavioral Reviews* 35 (2), 241–250. doi: 10.1016/j.neubi.2010.09.005
- Schneider, C. E., Lakatos, P., Kertész, Y., Porten, S., and Pons, A. (2019). Perceptual oscillations and rapid amplification of spikes. *Front. Cognitive Sciences* 12 (4), 106–113. doi: 10.3389/fcog.2019.00012
- Schneider, C. E., Wilson, D. A., Radem, T., Scherbaum, R., and Lakatos, P. (2020). Oscillations of action timing and perceptual selection. *Curr. Opinion Neurobiology* 62 (1), 172–176. doi: 10.1016/j.conb.2020.02.001
- Slaby, J. (2018). "Resonance and the embodied mind," in *Collective emotion* (Oxford: Clarendon Press), 23–46.
- Slaby, J. (2019). "Atmosphere – a Schenker moment and beyond," in *Mind as atmosphere: 1* (New York: Routledge), 270–285.
- Slaby, J., Malinoff, R., and Wüchrich, P. (2019). "Affective arrangements," *Front. Neurosci.* 13, 1–12. doi: 10.3389/fnins.2019.00012
- Spiek, T., de Lange, F. P., and Jensen, O. (2014). Local enhancement of alpha oscillations by visual stimuli causes cyclic modulation of perception. *J. Neuroscience* 34 (36), 11871–11881. doi: 10.1523/JNEUROSCI.3873-14.2014
- Thelen, E., and Smith, L. B. (2001). *Adapt. New York, NY: Preprint*.
- Thelen, E., and Smith, L. B. (2008). "Dynamic systems theories," in *Handbook of child psychology: theoretical models of human development*, Editors E. M. Lerner and W. Damon (John Wiley and Sons, Inc), 238–312.
- Thelen, E., Bates, J. A. S., and Papil, A. (1997). Self-organizing systems and motor motor development. *Dev. Review* 17 (1), 59–87. doi: 10.1006/ddev.1997.0048
- Thompson, E., and Stapleton, M. (2009). Making sense of sense-making: reflections on creative and extended neural theories. *Cogn. Sci.* 33 (4), 601–614. doi: 10.1080/03616970903404412
- Thompson, E., and Varela, F. J. (2001). Radical embodied action dynamics and consciousness. *Neural Cognitive Sci.* 3 (3), 415–427. doi: 10.1080/104658100100017962
- Tulacher, W., Gerschlager, S., Ramakrishnan, S., Toulou, M., Wad-Petersmann, M., Schott, C., et al. (2021). Affective synchronies in live concerts illustrate the embodiment of music experience. *Sci. Reports* 11 (1), 14603. doi: 10.1038/s41598-021-01663-2
- Tulacher, W., Gerschlager, S., Witting, C., Wad-Petersmann, M., Ramakrishnan, S., Schott, C., et al. (2022). Topological entanglement synchrony in classical concert hall with human experience and aptitudes. *Sci. Reports* 12 (1), 16472. doi: 10.1038/s41598-022-07377-2
- Tulacher, W., Toulou, M., and Witting, C. (2020). Music synchronies in the bodies of an orchestra. *Front. Music* 2 (1), 209–219. doi: 10.3389/fmus.2020.00019
- van Dijk, L., and Barfield, E. (2014). Programming environmental practice to our understanding of affordances: the affordance-environment framework. *Front. Psychology* 5, 1000. doi: 10.3389/fpsyg.2014.00100
- van Gool, T. (1998). The dynamical hypothesis in cognitive science. *Behavioral Brain Sciences* 21 (Pt. 2), 615–616. doi: 10.1017/S0014052500004711
- Varela, F. J. (2010). Perceptual cycles. *Front. Cognitive Sciences* 13 (10), 723–739. doi: 10.3389/fcog.2010.00039
- Varela, F. J. (2014). Attention cycles. *Front. Neurosci.* 8, 432–444. doi: 10.3389/fnins.2014.00432
- Varela, F. J. (2015). The oscillating body: an enactive approach to the embodiment of emotions. *Rev. De Neurosci* 26 (4), 317–327. doi: 10.1016/j.neurosci.2015.03.004
- Varela, F. J. (2021). "Why is 'I' always an abstracted feeling of 'it'?" in *Frontiers in Human Neuroscience*, 15, 6821076. doi: 10.3389/fnins.2021.6821076
- Varela, F. J. (2021). *Enactive cognition*. Milan, Italy: Adelphi Editore.
- Varela, F. J., Rosch, E., and Thompson, E. (1991). *The embodied mind: experience and human cognition*. MIT Press.
- Varela, F. J. (1996). Resonance and oscillation: a new approach to cognitive functions and neuronal synchrony. *Dev. Rev.* 16 (1), 61–81.
- Varela, F. J., and Rock, D. E. (2017). Rhythms of the body, rhythms of the brain: integration, neural oscillation, and embodied cognition. *Cognitive Sciences* 36, 73–86. doi: 10.1080/03616970.2017.1300008
- Varela, F. J. (2020). Atmosphere and extended beings. *Phenomenology and Cognitive Sciences* Preprint. doi: 10.1007/s10992-020-09574-4
- Varela, F. J., and Pihlak, P. (2021). "What are atmospheres?" in *The philosophical quarterly*.
- Warren, W. B. (2006). The dynamics of perception and action. *Psychol. Review* 113 (2), 354–369. doi: 10.1037/0033-295X.113.2.354



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Emotive cities: understanding human perception of urban spaces – a pilot study

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Neurourbanism offers new ways to understand how urban environments shape human cognition and emotion, yet empirical studies in rapidly urbanizing regions like South India remain scarce. This pilot study investigates how diverse urban settings in Calicut, Kerala, influence neurophysiological states using mobile-EEG technology. Participants navigated urban spaces varying in street enclosure, natural features, and activity levels, with EEG readings analyzed for emotional states including excitement, engagement, interest, relaxation, and stress. Results show significant shifts in these metrics as environments transitioned from busy to calm, narrow to wide, urban to green, and crowded to less occupied. This study is the first to apply mobile EEG in a South Indian context, highlighting the potential for evidence-based urban design to enhance mental wellbeing. Findings underscore the importance of integrating green spaces, optimizing street scale, and promoting walkability in urban planning, with implications for policy and design practice in developing cities.

KEYWORDS

emotions, human behaviour, neurourbanism, South India, urban design

1 Introduction

Rapid urbanization in developing regions like South India intensifies the interplay between built environments and human cognition, invoking interest across psychology, neuroscience, and urban planning (Madsen, 1943; Andrews, 1975; Kaplan, 1980; Chung et al., 2009). Previous studies in the field of cognitive sciences and neurourbanism have revealed compelling traces of the relationship between neuroscience and the built environment by analyzing how neuroscience data can inform the design of a better built environment by understanding its cognitive foundations (Mansur et al., 2012; Seyer et al., 2014).

Urban environments elicit multiple, partly overlapping forms of human response, including physiological (e.g., hormonal changes, autonomic activation), psychological (e.g., perceived stress, mood, cognitive loads), and behavioural reactions (e.g., avoidance, walking pace, withdrawal into private spaces). Laboratory and imaging studies have shown that city living is associated with altered activity in stress-related neural circuits, such as the amygdala and cingulate cortex, pointing to heightened physiological sensitivity to social and environmental demands (Krubandian et al., 2020; Enderbogan et al., 2011). At the same time, epidemiological and survey-based work links urbanicity to increased psychological distress and mental health risks (Hightow, 2025), while observational and environmental psychology studies document behavioural adaptations such as reduced public space use or preference for quieter, greener routes (Jin et al., 2022; Ludwig, Lauenbach, and Zopf, 2021).

Although these response domains are interconnected, their exact causal relationships remain debated. Some models suggest that chronic physiological arousal may gradually shape psychological vulnerability, which in turn influences everyday behaviour, whereas

others emphasize bidirectional feedback between subjective appraisals, bodily states, and actions. For this reason, recent neurourbanism research increasingly combines physiological indicators (such as EEG or biomarkers) with self-reported experience and observed behaviour to better understand how specific urban settings are processed and evaluated by city dwellers.

The main objective of this research was to conduct pilot experiments to verify the possibility of capturing the psychological effects on participants as they move about in diverse urban environments. Ultimately, this research seeks to elucidate the cognitive foundations underlying the psychological impact of urban space. Most empirical work to date is based in Western or Global North cities, whereas rapidly urbanising contexts in South Asia remain under-represented. This experiment was a methodological pilot to investigate how well the mobile EEG measurement corresponded to the subjective experience of individual pedestrians on streets with diverse experiential atmospheres in a non-western large-scale urban environment.

2 Background

Human behaviour in urban public places is influenced by various attributes, such as physical, social, cultural, and sensory factors. Abraham Maslow's Hierarchy of Needs suggests that physiological, biochemical, or aesthetic requirements, safety, love and belonging, and desire for self-actualisation, status or esteem are essential variables in driving behaviour (Maslow, 1943), based on primitive survival instincts. Appleton's Habitat Theory hypothesizes that human aesthetic preference is rooted in our evolutionary history as both hunter and prey. Specifically, it suggests that we derive pleasure from landscapes that offer "prospect"—open views for surveying threats or escape routes—and "refuge"—concealed vantage points, such as trees or vegetation, for safety and strategic observation (Appleton, 1977). Kaplan's Attention Restoration Theory (ART) suggests that exposure to natural surroundings supports more effortless brain activity, allowing it to heal and refill its focused attention capacity (Kaplan, 1995). Spatial scale and enclosure critically mediate these influences, with narrower streets accelerating social interaction and perceptual engagement compared to wide arterials (Owens, 2022). In developing cities, even small-scale vegetation like home gardens provides accessible restorative benefits, supporting mental health in dense urban contexts (Gullattamara, 2022).

Urban spaces intentionally shaped with perceptual cues deliver high-intensity multisensory inputs—traffic, pollution, noise, sights, chaos—that elevate basal alertness, stress, and cognitive load, often prompting retreat to calmer private areas (Hollander et al., 2020b). These environments trigger interconnected physiological, psychological, and behavioural responses, though their precise linkages remain debated. Physiologically, urban stressors activate the hypothalamic-pituitary-adrenal axis, releasing cortisol and adrenaline to mobilize energy for threat response, chronic elevation impairs immunity and cardiovascular health (Neale et al., 2020; Russell and Lightman, 2019).

For those living in cities, the intensity of inputs, such as traffic, pollution, noise, odours, sights, chaos, and other stimuli, is higher. This can cause cognitive overload by elevating the body's basal levels

of alertness, stress, and preparedness, in addition to causing people to seek comfort in calm private areas. This inclination may ultimately lead to social isolation, which is linked to anxiety and depression. Neuroimaging confirms heightened amygdala (emotion processing) and cingulate cortex (negative affect regulation) activity among city dwellers, with urban splintering amplifying perigenual anterior cingulate responses regardless of current residence (Lebelogou et al., 2011; Hollander et al., 2020a). Psychologically, this manifests as elevated perceived stress, anxiety, and reduced attention restoration, while behaviourally, individuals exhibit avoidance of crowded spaces or preference for quieter routes.

Psychophysiological measurements have been formulated based on the premise that physiological indicators reflect an individual's psychological state. The advent of inexpensive and portable EEG equipment has opened new avenues for architects, planners, psychologists, and neuroscientists to assess subjective experiences and understand the foundation of human behaviour in architectural and urban settings (Morris et al., 2012; Berry et al., 2011). Mobile EEG provides non-invasive means of collecting people's emotional states as they move about their surroundings, allowing scientists to determine which brain areas are active and their part in human behaviour (Hollander and Turner, 2016; Guedes Brenes and Lee, 2016). In urban design, mobile EEG can help to better understand how people interact with their surroundings, assist the design process, and analyse how places work. Mobile EEG devices have been used in environment preference studies, where 29 participants were asked to observe images of urban and natural environments on a computer screen and register their eye-tracking and EEG responses simultaneously while recording their subjective responses (Chung et al., 2006). Higher levels of local green space were linked to considerably lower levels of depression, anxiety, and stress symptoms.

Neurourbanism, a field of study that combines neuroscience and urban disciplines, has emerged as a new academic discipline that focuses on the interdependencies between urbanisation and mental health (Adli et al., 2017). A report published in collaboration with the Central Lab and University College London demonstrates the potential of neuroscience in the built environment, including how it interacts with emerging technology, employs and qualifies urban planning theory, and provides insight into improving city user experience, leading to increased productivity, well-being, and desirability (Kamargo et al., 2016). Experimental studies have emerged in neurourbanism, with the first real-time observation supporting the literature that confirms the association of beta wave frequencies with active decision-making or other intense cognitive functions or stress (Namasudran and Turner, 2017; Neale et al., 2020; Erfani, 2018; Chavesda Gomes et al., 2018; Ducan et al., 2018).

3 Studying pedestrian movement

Walking is a popular scientific subject because of its health benefits, socioeconomic advantages, and environmental exposure. Walking focuses on the embodied experience with the senses and allows for the study of surroundings (Pursons et al., 1998). Walking enables multi-sensory engagement with constructed, natural, and social surroundings at pedestrian scale, facilitating nuanced

psychological responses that stationary observation cannot capture (Sart et al., 2023). Pedestrians see and engage with constructed, natural, and social surroundings because of their modest pace and close proximity to buildings and people (Gadi et al., 2005). Environmental psychology studies have used naturalistic walking to examine the psychological effects of urban and natural settings. The “restorative” benefits of natural settings, such as parks or forests, have been a key area of research. Restorative theory suggests that green and natural environments have a positive psychological impact, making it easier to recover from stressful events or to restore cognitive function (Pett et al., 2019).

Recent urban design research similarly emphasizes how street-level spatial configuration shapes user experience and social dynamics (Amm and Nis, 2021). Researchers have increasingly used naturalistic experiments with walking participants to explore the potential positive psychological effects of short-term visits to natural environments (Thompson et al., 2014). Early experiments used self-reported measures, such as the Perceived Restorativeness Scale, and more recently, mobile psychophysiological measurements of people’s mental states. Research in the psychological effects of the environment has progressed from tightly controlled, visual exposure of various environmental scenes to situated and often mobile experiments of people walking “in the wild.”

4 Methodology

4.1 Materials

4.1.1 Data acquisition and instrumentation

The experiment employed the Eotiv Insight, a wireless, portable 5-channel wireless header (AF3, AF4, T7, T8, Pz) with a sampling rate of 128 Hz and 16-bit resolution designed to capture real-time brainwave activity during participant movement in outdoor urban settings (Immon, 2023). This device records multiple frequency bands (delta, theta, alpha, beta, gamma) with onboard algorithms mapping these signals to performance metrics including engagement, excitement, interest, relaxation, and stress. This device was selected for its high portability and validated utility in ambulatory research settings where traditional tethered systems are impractical (Laricco et al., 2020). Data were transmitted via Bluetooth to a laptop carried by the investigator always maintaining proximity within wireless range. All equipment was cleaned and sanitized before and after each session to prevent contamination between participants.

4.1.2 Survey and interview instruments

The study utilized three self-report instruments: a pre-experiment survey, a post-experiment survey, and semi-structured interviews administered during post-experiment debriefing. Participants completed a demographic questionnaire administered prior to device fitting, collecting information on age, gender, professional background, geographic origin, and prior familiarity with urban walking. This brief survey (~5 min) used open-ended and closed-ended items and established context for interpretation.

Immediately following each walk through a specific urban area, participants completed a location-specific Likert-scale survey. Each

performance metric (stress, engagement, interest, excitement, focus, relaxation) was rated on a 5-point discrete scale with anchors: “Not at all” (1), “Slightly” (2), “Moderately” (3), “Very” (4), and “Extremely” (5). Questions like “How engaged did you feel while walking through this street?” and “How stressed did you feel during the walk?” were asked. This structured approach enabled direct comparison with EEG-derived metrics while maintaining consistency across all participants and locations.

After completing each location-specific survey, participants engaged in brief semi-structured interviews (1–5 min per location) to provide qualitative context for their emotional experiences. Investigators used standardized open-ended prompts including “Please describe what you experienced emotionally while walking through this street,” “What specific environmental features (e.g., sounds, sights, vegetation, traffic) most influenced your feelings?” and “How would you characterize the overall atmosphere or mood of this place?” Responses were audio-recorded (with explicit participant consent) and subsequently transcribed verbatim for thematic analysis. These qualitative data complemented and enriched the quantitative EEG and Likert-scale findings, allowing participants to articulate nuances in their affective experiences not fully captured by numerical metrics alone.

4.2 Technology used

Existing studies that summarise neuroscientific assessment systems or investigations of the built environment are primarily concentrated in the Western world, using technologies such as eye-tracking, fMRI, and EEG to explain or evaluate human experiences in public places (Matten et al., 2016). However, fMRI equipment is bulky, noisy, and imposes posture constraints for participants, such as lying horizontal and still for the duration of the experiment. On the other hand, EEG is less restrictive, lightweight, wireless, and its new analytical tools have become increasingly tolerant of head and body movements, even allowing participants to walk freely. The advent of mobile EEG has resulted from the minimization of the signal amplifier and the use of wireless protocols for data transfer from the head-mounted amplifier to an auxiliary recording device such as a desktop or tablet computer. This eliminated the need for long electrode leads and allowed participants to be involved in tasks with higher ecological validity, whether static (seated, screen-based) or active (walking, moving). Although consumer-grade mobile EEGs are rather limited in terms of electrodes, targeting only areas of the brain that are of interest for applications such as gaming or neurofeedback, they have spurred many applications within and beyond neuroimaging. Neurofeedback is a procedure in which a user receives information (feedback) in real time about his/her brain activity and deliberately attempts to control the brain’s electrical activity (Grazzini, 2014).

Notably, the contemporary landscape of brain-computer interface technology has undergone significant transformation, democratizing access to tools like the Eotiv Pro. This software, easily accessible to a wide array of disciplines, facilitates the interpretation of EEG signals captured from mobile EEG devices. There are different types of brainwaves that the EEG measures. Raw EEG signals can be identified as distinct waves with different frequencies. Raw EEG signals are often quite noisy and require

TABLE 1 Performance metrics and bandwidth relationship.

Metric	Definition	Relationship with bandwidth
Flow (FR)	Measurement of beta amplitude in a participant's walk or gait task.	Elevated beta activity and reduced alpha and theta activity are indicators of stress and distraction.
Engagement (ENG)	Attention and cognitive directed of attention towards task-related stimuli.	Measured primarily through beta and gamma activity. High beta and gamma waves indicate higher engagement and cognitive workload.
Arousal (AR)	Degree of activation or arousal in current stimuli, environment, or activity.	Closely correlated with patterns in beta and gamma activity, similar to engagement, indicating mental stimulation and arousal.
Excitement (EX)	Intensity or feeling of physiological arousal with a positive valence.	Associated with increased beta and gamma activity, reflecting intense and heightened emotional states.
Focus (FOC)	A measure of focal attention on one specific task.	Strongly linked to beta wave activity, indicating sustained attention and concentration.
Relaxation (REL)	Measure of an ability to switch off and recover from intense concentration.	Higher alpha and theta wave activity are indicators of relaxation and meditative states.

preprocessing to remove artifacts caused by blinking of the eye, muscle activity, or electrical interference. Band-pass filters are applied to remove noise outside the frequency range of interest and certain algorithms are applied to remove the artifacts. Once the signals are cleaned, the power in different frequency bands are analyzed to classify them into delta, theta, alpha, beta, and gamma bandwidths along with time domain and time-frequency analysis. This helps to extract features that can be used to quantify different brain states. Techniques such as Principal Component Analysis (PCA) or other dimensionality reduction methods are applied to reduce the dimensionality of the data and focus on the most relevant features. These data are then fed into the classification algorithms that map them to specific performance metrics.

Although this is a tedious process, researchers are now empowered to decode and classify these signals into mental states, such as engagement, excitement, and stress, thereby enabling interdisciplinary studies within the realm of built-environment research without necessitating a comprehensive background in raw EEG analysis. EmotiV's algorithms analyse the power spectrum of these frequency bands in real-time to classify cognitive and emotional states. For instance, increased power in the beta band might be interpreted as high engagement, whereas increased alpha power might be interpreted as relaxation. The exact thresholds and combinations of these frequencies are determined through machine learning models trained on extensive datasets of EEG recordings under various conditions. The EmotiV Pro software categorizes these waves into six different measurable cognitive states called performance metrics. These performance metrics are described in the following table (see Table 1).

The performance metrics explained in Table 1 were used to interpret the human brain waves into the current mental state of the participant as they traverse through various urban spaces. A preliminary behavioural experiment was conducted as a pilot study in which multiple participants underwent naturalistic walking through designated streets within familiar destinations with the objective of discerning meaningful patterns among the participants. It should be noted that the data collection took place in real-world environments, with participants actively engaged in walking in all experimental situations.

4.3 Procedure

4.3.1 Participant recruitment and informed consent

Participants were recruited through social media posts and poster circulation targeting adults aged 25–45 with diverse professional backgrounds and geographic origins in or near Calicut, India. A recruitment notice was disseminated via social media networks, explaining the study purpose, procedures, time commitment (1–90–120 min per session), and equipment used. Interested individuals contacted the principal investigator to arrange a session. Informed written consent was obtained before the start of any procedures. The consent form included a detailed project briefing, FAQ section addressing equipment safety and data privacy, and explicit authorization for audio recording and potential use of anonymized data and photographs in publications. Participants were informed of their right to withdraw at any time without penalty.

4.3.2 Pre-experiment preparation

Upon arrival, participants completed the pre-experiment demographic survey in a quiet environment (1–5 min). They were then escorted to a private parked vehicle where the EEG device fitting took place in a controlled, comfortable setting. During this fitting phase (1–15 min), the investigator explained how the EmotiV insight operates, answered participant questions, and ensured proper electrode-scalp contact across all five channels (As seen in Figure 1). Participants were informed that the device is wireless, non-invasive, and safe for walking. The investigator then guided participants into a calm, meditative mental state by requesting they close their eyes and breathe slowly for 3–5 min while EEG signals were monitored on the EmotiV Pro software. Once the participant demonstrated stable alpha and theta activity consistent with baseline relaxation, baseline EEG data were internally recorded (1–5–8 min), serving as the individual's reference state for subsequent comparisons during walking.

4.3.3 Experiment

Upon baseline completion, participants were instructed to begin walking through the first designated urban area. The walking session proceeded according to a standardized protocol (See Figure 2).



FIGURE 1

Topographic layout and the location of 16 sensors.



FIGURE 2

Process of the experiment.



Walk Phase (~10–15 min per location): Participants traversed a predetermined route through the assigned street while wearing the active EEG device. The principal investigator walked at a safe distance behind the participant (sufficient to remain visible and within Bluetooth range of the device, typically 5–10 m). Participants were explicitly instructed not to speak during the walk to minimize electrode artifact from jaw movement and vocal cord activation. The investigator carried a laptop connected via Bluetooth to the EEG device, monitoring signal quality and data continuity throughout the walk (Figure 1). The investigator also discretely observed and noted participant behaviour and any environmental anomalies (e.g., unexpected traffic, weather changes, or equipment malfunction).

Pause and Survey Administration (~5–10 min per location): Upon completing the walk through a specific urban area, participants paused in a nearby shaded or sheltered area. The

investigator administered the post-experiment Likert-scale survey questionnaire, which participants completed independently. The EEG device remained fitted during this survey period, allowing for continued data recording during the transition between active movement and reflective assessment.

Semi-Structured Interview (~5–10 min per location): Immediately following survey completion, the investigator conducted a brief face-to-face semi-structured interview using the standardized open-ended prompts listed above. Participants were encouraged to speak freely about their emotional and sensory experiences during the walk. The investigator audio-recorded all responses using a portable digital recorder (with explicit prior consent) while taking brief written notes to capture contextual observations. No responses were solicited or prompted beyond the initial open-ended questions, allowing participants to articulate their experiences without undue influence.



Figure 3
A portion of the experimental setup to which the participant is walking on a selected street.

4.4 Site

The intention of this pilot study is to ascertain if there exists a discernible pattern among participants as they navigate different urban settings. Given that this study is in its initial stages, three distinct locations within Calicut city, Kerala, India each exhibiting unique urban characteristics, were chosen for the experiment.

1. **Street A – Beach Road.** An active urban thoroughfare with juxtaposing urban structures against an active and vibrant

coastal backdrop with approximately 800 m. of walking distance (Figure 4).

2. **Street B – Aswathyam Mini Bypass.** An urban green street featuring a water body and lush greenery along one side and moderate traffic and buildings on the other side. It has a walking distance of approximately 900 m (Figure 5).
3. **Street C – Marrow Road.** A bustling urban street lined by buildings on both sides with high-intensity traffic and footfall. It has a walking distance of 700 m (Figure 6).

All participants navigated the same three locations in an identical, fixed sequence to ensure environmental and temporal consistency. Sessions were conducted during non-monsoon morning hours (08:00–11:30 a.m.) to minimize weather-related confounds and ensure consistent daylight conditions. The same time was chosen for each location to minimize time-based weather/temperature fluctuations. Between each location, participants were permitted a 3–5 min rest period to recover, though ECG recording and subsequent survey/interview administration proceeded immediately upon arrival at the next area.

This study employed a within-subjects experimental design wherein all participants experienced all three urban environments in an identical, predetermined sequence. This design was chosen to maximize internal validity by ensuring that individual differences in demographics, neurobiology, or familiarity with walking were controlled for through repeated measurement within each person. The fixed order presentation of locations, while introducing potential order effects, was operationalized



Figure 4
Participant was first image of Street A next to satellite image of the surroundings.

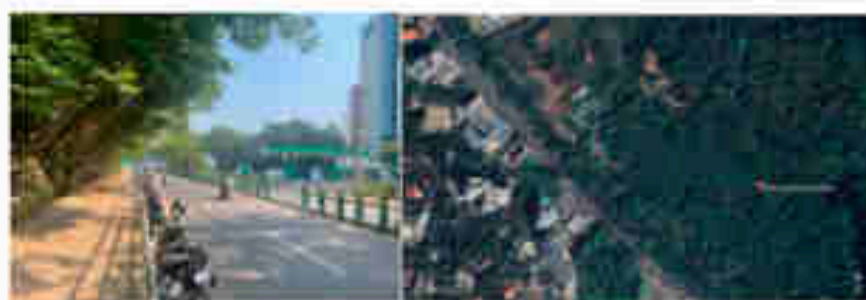


Figure 5
Participant was first image of Street B next to satellite image of the surroundings.



FIGURE 5
Participant eye shot image of Street A next to roadside of the 5th round (2).

intentionally to standardize the experimental context and enable robust statistical and qualitative comparisons across the small pilot sample.

4.5 Qualitative analysis protocol

All semi-structural interviews were audio-recorded with participant consent. Recordings were subsequently transcribed verbatim by the principal investigator within 48 h of the session to ensure accuracy and minimize memory loss. Transcripts were reviewed for clarity and completeness. The transcribed interview responses were coded inductively to identify emergent themes related to emotional experience, environmental perception, and sensory responses. Themes were organized by participant, location, and perception to enable triangulation with quantitative EEG and survey data. This approach allowed qualitative responses to contextualize and validate the numerical findings. All audio recordings, transcripts, and EEG data were stored on a password-protected, encrypted drive accessible only to the principal investigator. Participant identities were replaced with anonymous participant codes (e.g., P01, P02) in all data files and analyses. Interview excerpts cited in results were anonymized prior to publication.

5 Results and discussion

The pilot study included a stratified sample of individuals from whom the final readings were obtained. The experiment involved a representative sample identified from the age group of 25–45 years with participants of various genders and professional backgrounds. Their professional backgrounds spanned a range of fields, including fitness training, education, architecture, research, and technical expertise. Of the eight participants who participated in the study, data from two people had to be discarded due to inconsistent contact of the electrode on the scalp in the EEG experimental setup, leading to discontinuity and missing data in the readings. The final data from six participants (four men and two women) from a diverse demographic mix were obtained. Additionally, the participants exhibited varying geographical backgrounds, with three being

native to the study city and the remaining three originating from a different city.

The mean values for each performance metric were calculated for the six participants at each examined site. It is revealed that when analyzing the experimental results, they have a clear pattern as far as street characteristics are concerned. The excitement levels of Street A, located along the beachside, had a (see [Figure 7](#)) higher mean values ($\text{Ex}_A = 68.2$) showing the increased physiological arousal and awareness. Also, it was noted that this street had the highest mean interest value ($\text{In}_A = 71.5$), indicating greater attraction and reduced aversion to its environment. There is a relative lack of focused attention on any specific activity which may be inferred from $\text{Fo}_A = 28.1$ which is the average focus value for this street. This could be due to increased liveliness and dynamism in the beach area, leading to increased arousal and attraction levels. Furthermore, it could be argued that this setting offers a feeling of ease which might reduce the cognitive load during walking, thereby lowering focus. In the post-experiment survey, the participants described the walk as Relaxing and exciting walk. The view to the beach was highlighted in most responses. Few of the responses said “had a mix of built-up and green open spaces throughout the stretch. The urban design features such as landscapes, pedestrian paths and street designs captured interest at various points” “It was interesting to track my feelings while I focused on experiencing the space I was walking through. It was obvious that my level of interest and excitement would go up as I passed through shades and greenery.” Another respondent said, “The route areas with trees and landscape felt more relaxing and positive. It is nice walking with the view of beach.”

However, Street B which contained much green, had relatively higher mean values of excitement ($\text{Ex}_B = 63.7$), interest ($\text{In}_B = 64.5$), and relaxation ($\text{Re}_B = 56$). The presence of trees and water bodies seemed to promote increased relaxation, physical arousal, and interest levels. This aligns with findings that incidental greenery in developing urban settings yields measurable psychological benefits ([Sulloymannala, 2022](#)). Participants described the walk along Street B as very peaceful and calm experience. One participant said, “The walk was comfortable and felt rather relaxed and safe. The green landscape and the canal caught my attention more than the busy roads which made the walk enjoyable.” But few participants also said, “It is very calm and serene atmosphere, but the water is too muddy and unpleasant.” “I had

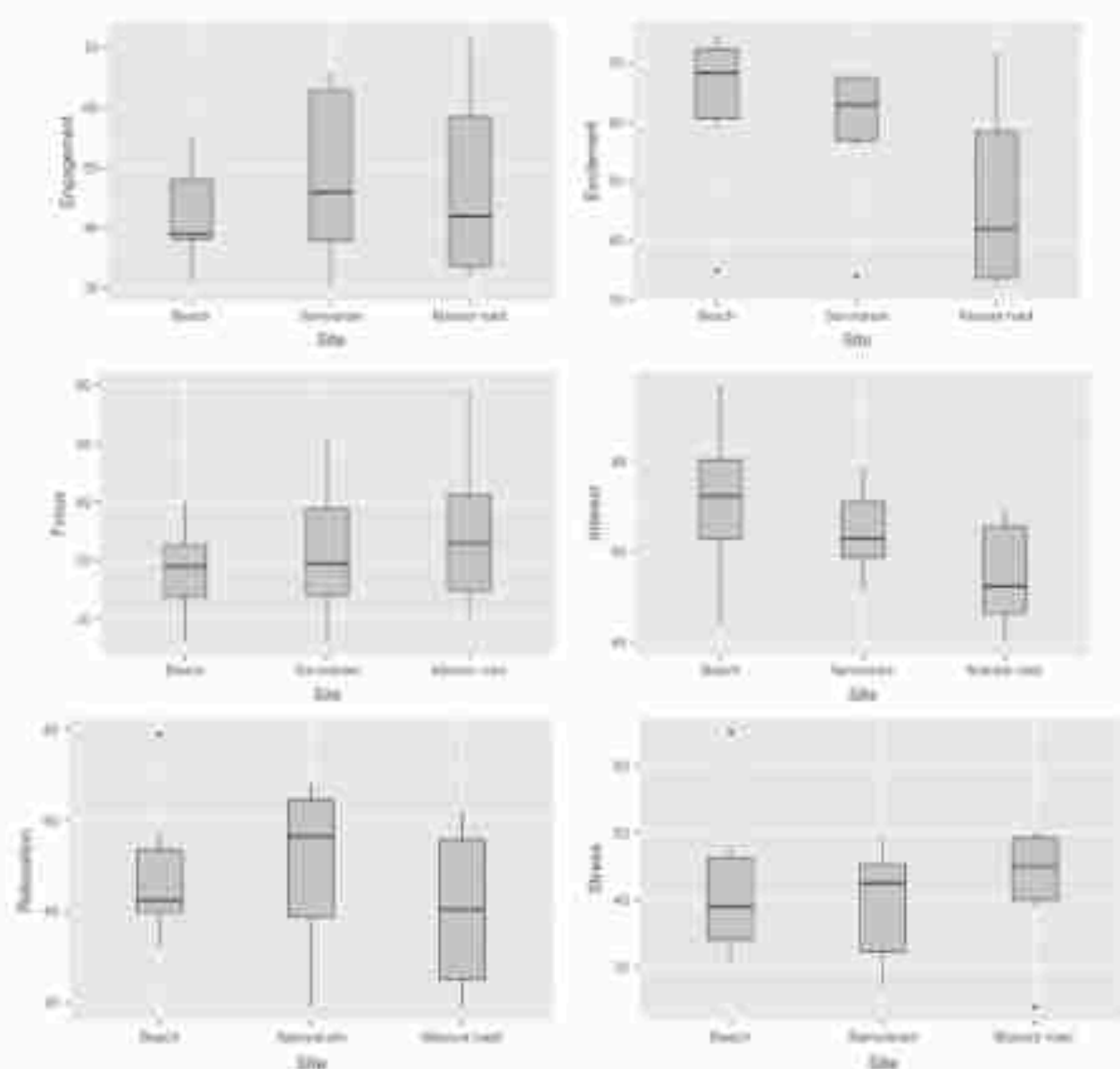


FIGURE 1 | Box plots showing the distribution of each performance metric across three sites.

a great time doing that experiment. In the beginning, the smell was not good (i.e., my attention was on the water feature and wondered if it was polluted, I also looked at the large and wild flocks of the trees.)

Street C is characterized by busy roads and buildings lining both sides, thus exhibiting lower mean feelings of excitement ($E_x, C = 42.2$), interest ($I_n, C = 54.8$), and relaxation ($R_x, C = 40.5$). However, the average focus value in this context was significantly higher ($F_x, C = 55.3$). This indicates that there was a reduced response to arousal, attraction, and relaxation, accompanied by increased attention to walking tasks. Several factors could explain such observations, including distractions from vehicular traffic and the absence of green spaces which can potentially increase the cognitive load. Moreover, the absence of vibrant activities in this environment may infer monotony with more concentration felt during walking. Participants responded that walking along street C felt was not very

pleasant and it made them very alert and stressed. Many described it as "too loud and noisy." One participant was worried about the crowd on the path, and said "I understood that I'm better off with very less people around me." Another participant said, "Things that caught my attention were the new bus waiting shed on the opposite side of the road and a single tree near the junction at the end of the designated stretch." One participant wondered if walking above the slabs that covered the drainage was safe.

This study has shown that urban environments are intricately linked to people's psychophysiological responses. The elevated relaxation on the green corridor (Street B) and the combination of interest and excitement on the coastal street (Street A) reflect Kaplan's prediction that natural and semi-natural environments afford "soft fascination," allowing cognitive recovery while maintaining engagement (Kaplan, 1995). The reduced stress and

sustained positive affect on these streets support ART's predictions about restorative environments. The elevated engagement on the narrower, more enclosed Beach Road aligns with research on spatial scale and social perceptual engagement. Already existing studies documents that moderate enclosure and legible spatial configuration heighten social and perceptual engagement compared to wide, monotonous arterials (Larson, 2002; Ameen and Nix, 2021). Our findings suggest that this effect extends to neurophysiological indices of engagement and interest, not merely self-reported perception. The heightened focus coupled with low relaxation on the busy commercial street (Street C) accords with literature documenting that high environmental complexity, noise, and crowding elevate cognitive load and trigger defensive, task-focused attention (rather than exploratory engagement) (Kumudhara and Tumm, 2017). The absence of restorative features (greenery, open space, quietude) appears to offer no compensatory benefits. The outcome shows how important different environmental elements like natural features, level of activity and the kind of audience are when it comes to influencing emotional states and cognitive engagement during walking.

6 Limitations

The study serves as a proof-of-concept that mobile EEG walking studies are feasible in non-Western urban settings. It identifies practical challenges, environmental confounds and solutions like pre-walk briefing, outdoor device fitting, standardized routes, etc. Future, larger studies can build on these protocols. The work does not claim to definitively establish causal relationships between specific street features and cognitive-emotional states. Rather, it generates plausible patterns that motivate future investigation with larger samples, multimodal sensing (EDA, HRV, environmental monitoring), and more sophisticated statistical models.

This pilot study had a few practical challenges including time-consuming data collection and analysis, the possibility of sensor disconnecting due to movements by participants and fluctuations in EEG readings from sudden distractions in the environment. The fluctuations in participants' EEG readings because of minor environmental factors such as weather changes, traffic and day time must be considered thoroughly hence large sample sizes may be required for this. Moreover, logistical challenges like short laptop battery life reduces the number of experiments that can be conducted at a given time. Additionally, coordinating data based on volunteer availability add further complexity to the research process.

Moreover, it is important to acknowledge that Calicut City, being a small urban area in South India, presents a distinct set of urban and environmental conditions. Due to its urban form that is mostly low-rise buildings and homogeneous in nature, the city may offer limited variability in environmental stimuli compared to larger and more diverse urban areas. The lack of designated urban public spaces in the city limits the range of varied environments available for data collection and affects the generalisability of findings. With its tropical climate, the city experiences extremes of sunshine and heavy rainfall, which may influence participant behavior. Environmental factors, such as relative humidity, noise levels and

air quality can possibly introduce confounding variables into the study.

Being a pilot study intended to validate a methodology, the sample size chosen was small. Such small sample size could affect internal validity of the result. Nonetheless, this constraint presents an opportunity for further investigation in the relevant study area. Studies with larger sample sizes would be able to tackle this problem more effectively, perform better randomisation, and control the effect of confounding variables. Strategies to reduce randomisation bias, such as using stratification techniques in participants, are recommended to improve the reliability and validity of future research outputs.

Potential influences of participant characteristics such as gender, age, familiarity with the city, and transient states (e.g., sleep quality or daily mood) were not examined statistically in this pilot and remain uncontrolled sources of variance. Future studies with larger samples should explicitly measure these variables and incorporate them as covariates or factors to better disentangle individual differences from environmental effects.

The advantages of using multiple EEG techniques simultaneously on participants in similar studies are that it can optimise time efficiency and increase the rate of data collection. It helps researchers to gather more information over a wider sample size in a shorter period thereby boosting the statistical power as well as reliability of the results. It also allows researchers to control the environmental variables more effectively. By exposing participants to the same environmental conditions simultaneously, the impact of external factors such as weather, traffic, and other variables can be reduced or accounted for in the analysis. Researchers can observe how different individuals respond to the same stimuli and change in visual characters.

Subsequent studies with larger and more diverse samples can build upon our findings, employing more sophisticated randomisation techniques and enhancing the reliability and validity of the results. Exploring alternative study designs or methodologies that mitigate the impact of small sample sizes could provide further insight into the complexities of the study.

7 Conclusion

This research, however, sheds light on the underlying dynamics that exist between urban environments and the psychophysiological responses of individuals, thus providing insight into what influences and affects individuals' mood, cognitive functioning, and overall mental health. The findings reveal that pedestrians walking through active streets or natural features on at least one side experience increased positive psychological stimulation compared to those living in densely built areas. This study reveals that green spaces in the city and proximity to nature were found to have positive effects on mental health. These natural features have restorative qualities that help diffuse the stress of city life. This study calls for the incorporation of green spaces in urban planning and design because of their contribution to improving mental wellbeing. The results also indicate that incorporating a natural environment into the urban streets of a city or any other urban setting will result in lower stress levels among its inhabitants. Lively urban streets create interest and engagement in various activities, thus contributing positively to the urban experience in general.

Collectively, this study underscores the multifaceted benefits of urban planning strategies that encompass elements such as green spaces, natural environments, and diverse activities. By considering these factors, urban planners and policymakers can work towards creating more enriching and health-promoting urban landscapes that not only meet the physical needs of residents but also contribute to their psychological wellbeing. As cities continue to evolve, the insights gained from this study can serve as a foundation for the creation of urban spaces that foster healthier and more sustainable communities. The methodology of this pilot can be a stepping stone towards more meaningful research in this field.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Institute Ethics Committee, National Institute of Technology Calicut. The studies were conducted in accordance with the local legislation and institutional requirements. The study involved human participants and the collection of neurophysiological data using a wireless 5-channel EEG measuring device. The participants provided their written informed consent to participate in this study. Written informed consent was also obtained from the individuals for the publication of any potentially identifiable images or data included in this article. Additionally, data handling and analysis procedures were designed to protect the privacy and confidentiality of participants.

Author contributions

LM: Writing – review and editing, Conceptualization, Investigation, Methodology, Software, Visualization, Resources, Writing – original draft, Project administration, Validation, Formal Analysis, Data curation,  Supervision.

References

- Adk, M., Beggs, M., Bakkenes, E. L., Engel, L., Fagghini, J., Genter-Carroll, J., et al. (2017). Neurophysiology reveals new discipline. *Learn. Perspect.* 4 (1), 165–166. doi:10.1016/j.csl.2017.03.004
- Aiken, M. A., and Peng, H. A. (2011). “The effect of cognitive semantics on the interpretation of urban space configuration,” in *4th International Conference of Contemporary Affairs in Architecture and Urbanism (ICCAUA-2011)*, 24–31. doi:10.1007/978-3-70-912708-9
- Anderson, J. H. (1973). The experience of landscape. *Landscape* 14 (1), 15–19. doi:10.1080/014487973087310796
- Appleton, J. (1975). *The experience of landscape*. John Wiley and Sons Ltd.
- Baker, K. M., Kellenbach, A., Tobi, A., Beggs, M., Allen, E. J., and Myles, R. M. (2014). Exposure to neighborhood green space and mental health: evidence from the survey of the health of Wisconsin. *Int. J. Environ. Res. Public Health* 11 (1), 3455–3472. doi:10.3390/ijerph110503455
- Carrozzini, A., Bionini, F., Akkoy, S., Althoff-Collado, D., and Arino, J. (2018). Neuroscience, urban regeneration and urban health. *J. Urban Reg. Res.* 12 (1), 201–208. doi:10.1080/17447740.2018.1464026
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- Cheng, C. Y., Hancock, W. E., Chen, P. K., MacDonald, L., and Li, W. C. (2009). Psychophysiological responses and restorative values of natural environments in Taiwan. *Landscape Urban Plan.* 87 (1), 79–84. doi:10.1016/j.landurbplan.2007.04.018
- Dumas, A., Koen, T., and Gao, Z. (2014). “Neuroimaging: validating multimodal cognitive data in the city towards a model of how the urban environment influences intelligence tests,” in *Proceedings of the Workshop on Modeling Cognitive Processes from Multimodal Data (MCP4D-2014)* (Seattle, Colorado: Association for Computing Machinery), 161. doi:10.1145/2579818.2579833
- Eghmorani, K. (2022). Urbanization and mental health: redefining public spaces to support wellbeing. *Int. J. Healthc. Sci.* 12 (1), 71–80.
- Emmett (2021). “Emmett (smart) User Manual: technical specifications.” 2020. Available online at: <https://www.emmett.com/products/smart/>
- Fukami, J. (2016). Examining wellbeing behaviours in architectural space using brain imaging with electroencephalography (EEG). *Archit. Sci. Res. J.* 3 (1), 430–436. doi:10.18869/18828.2016.123128

- Pett, A. R. L., Lemmer-Vermeij, L. L. J., and Kalkbrenner, L. (2019). Psychology and urbanity: a review of the recent literature from epidemiology to neuroimaging. *Constr. Psychology* 32 (4), 232–240. doi:10.1080/10447318.2019.1666048
- Quilley, C., Kiefer, A. J., and Rappold, S. (2015). Close association with buildings: Grand Rapids 3 miles inside. *Urban. Pl. Archit.* 12, 70–82.
- Quiedat-Bouss, M., and Lee, C. C. (2018). Brain responses to wilderness: exploring cognitive foundations for the design of urban spaces. *Front. Psychol.* 7 (2007), 3017. doi:10.3389/fpsyg.2018.01947
- Quinlan, J. H. (2014). EEG neurofeedback for improving performance: a review of cognitive and affective outcomes in healthy participants. *Neurosci. Biobehav. Rev.* 44 (July), 124–141. doi:10.1016/j.neubiorev.2014.08.025
- Rehder, L., and Tietze, V. (2014). Brain responses to architecture and planning: a preliminary neuro-imaging of the performance experience in Berlin. *NeuroImage Arch.* 30 (4), 54–60. doi:10.1006/niarch.2014.12149
- Rehder, L. B., Paddy-Leeming, A., Tietze, V., Tietze, V., Paddy, S., Jank, R. J. R., et al. (2019a). Cognitive responses to urban environments: behavioral responses to lab and field conditions. *Urban Des. Int.* 34, 612–646. doi:10.1080/13602011.2019.1612246
- Rehder, L. B., Tietze, V., Tietze, V., Tietze, V., and Paddy, S. (2019b). Analyzing usability through biometrics: insights into cognitive transportation through the use of eye-tracking simulation software. *J. Phys. Activity Health* 17 (12), 1133–1141. doi:10.1123/jpah.2019.0127
- Shi, L., Lu, W., and Shi, P. (2022). Psychology for green environment based on brain changes between while walking. *Front. Psychol.* 13, 888791. doi:10.3389/fpsyg.2022.888791
- Kaplan, S. (1995). The restorative benefits of nature: toward an integrative framework. *J. Environ. Psychol.* 15 (3), 169–182. doi:10.1016/0272-6460(95)00041-2
- Katschke, A., and Tietze, V. (2017). Architecture and neuroimaging: what can the EEG recording of transactions reveal about a walk through everyday spaces? *Int. J. Psychophysiol.* 119 (Suppl. 1), 254–265. doi:10.1016/j.ijpsycho.2017.03.009
- Kellm, M. (2022). The role of 'body' as the moderation of social interaction in urban space. *J. Contemp. Urban Aff.* 4 (1), 59–68.
- Kalkbrenner, L., von Vapp, M., Gamm, P., Kalkbrenner, G., Empson, L. A., van Oo, J., et al. (2019). Understanding urbanity: how neuroimaging methods help to uncover the effects of the city on mental health. *Psychol. Med.* 51, 1–12. doi:10.1017/S0033291819000443
- LaFrance, J., Dong, L. M., and Puring, D. G. (2020). A systems review of available low-cost EEG hardware used for classroom detection. *Front. Neuroinformatics* 14, 553332. doi:10.3389/fninf.2020.553332
- Ludwig, F., Ritzke, P., Haidich, S., Stein, P., Tietze, V., Kiefer, A. J., et al. (2011). City living and urban upbringing affect neural social processing in humans. *Nature* 478 (7322), 484–488. doi:10.1038/nature10416
- Ludwig, C., Lauterbach, S., and Zieg, A. (2012). "Corruption of simulated fear and pain states for cyborg and pedestrians." In *Human-Computer Interaction for the Future* (Germany: Springer Publishing), doi:10.1007/978-3-642-28111-1_10
- Makris, A. H. (1993). A theory of human motivation. *Psychol. Rev.* 100 (1), 191–206. doi:10.1037/0033-2909.100.3.191
- Martens, P., Corne, R., Bos, L., and Aysa, P. (2012). *Edinburgh research explores the brain: engaging the brain*. Prague: Edinburgh Research Explorer.
- Martens, P., Aysa, R. E., and Smith, A. H. (2010). Geo-EEG: towards future of EEG in the study of urban behavior. *Appl. Spatial Analysis Policy* 3 (2), 109–112. doi:10.1007/s12060-010-9134-4
- Naale, C., Aysa, R., Bos, L., Tietze, V., Martens, P., Uebachs, S., et al. (2010). The impact of walking in different urban environments on brain activity in older people. *Cogn. and Health* 4 (1), 94–106. doi:10.1080/22780012.2014.910991
- Olshansky, G., Gao, S., Zou, X., Chen, J., and Yu, L. F. (2019). Window view and the brain effects of floor level and green cover on the alpha and beta rhythms in a positive exposure experiment. *Int. J. Environ. Res. Public Health* 16 (11), 2588. doi:10.3390/ijerph16112588
- Pietrowski, R., Tietze, V., G., Uebach, R. A., Tietze, M. R., and Gamm, A. (2019). The view from the road: implications for the stress recovery and restoration. *J. Environ. Psychol.* 78 (2), 113–126. doi:10.1016/j.jenvp.2019.03.006
- Raschütz, A., and Tietze, V. (2019). The human brain response. *Nat. Rev. Neurosci.* 20 (9), 525–534. doi:10.1038/s41573-019-0125-0
- Sun, M., Shi, P. F., Shi, P. F., and Hamburg, S. (2023). Psychological effects of walking and urban setting in urban green space during post-pandemic: a case study in Beijing city. *Urbanism & Community* 104 (2), 1–17. doi:10.1080/08904394.2023.2241111
- Stalpers, R. (2012). The role of home gardens in developing cities for improving urbanity. *Psychol. Case* 4 (2), 215–228. doi:10.1186/1745-6215-4-2
- Thompson, C. W., Aysa, R., and Bos, L. (2014). Access to green space in disadvantaged urban communities: analysis of behavioral effects based on biometric and self-report measures of well-being. *Psychol. Sci.* 25, 10–22. doi:10.1177/0956797614131756

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The multi-objective optimization of residential building glass in summer-hot and winter-cold regions using genetic algorithms: energy consumption, carbon emissions, and health performance analysis

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Introduction: With the growing demand for environmental sustainability and residential comfort, low-carbon buildings and healthy urban planning have become key research priorities. In summer-hot and winter-cold regions, the performance of residential building glazing plays a critical role in balancing energy efficiency, carbon emissions, and indoor health.

Methods: This study investigates the multi-objective optimization of residential building glass using genetic algorithms. Building energy consumption, carbon emissions, and indoor health performance are set as optimization objectives. Key glass parameters—including the window heat transfer coefficient, solar heat gain coefficient, and visible light transmittance—are optimized through a multi-objective genetic algorithm framework. Simulations are conducted using the Rhino and Grasshopper platforms, with Hangzhou, China, selected as the case study area.

Results: The optimization results indicate that annual building energy consumption decreases from 50.95 to 40.26 kWh/m²a, representing a reduction of 20.98%. Carbon emissions are reduced from 2622.93 to 2085 kgCO₂e/m², a decrease of 20.57%. In addition, the proportion of indoor healthy time increases from 34.46% to 40.9%, corresponding to an improvement of 18.69%.

Discussion: By comprehensively considering energy efficiency, carbon emissions, and indoor health performance, this study proposes an optimized glazing configuration for residential buildings in summer-hot and winter-cold regions. The results suggest prioritizing south-facing windows in building design, while adjusting glass parameters for other orientations according to specific conditions. This work provides practical technical support and optimization strategies for the development of low-carbon buildings and healthy cities.

KEYWORDS

genetic algorithms, high-performance glass, multi-objective optimization, energy consumption, carbon emissions, health performance

1 Introduction

As the issue of global climate change becomes increasingly severe, the building industry, as a major sector of energy consumption and carbon emissions, faces enormous challenges. The international community has reached a broad consensus. For example, the United Nations Sustainable Development Goals clearly require ensuring universal access to affordable and sustainable energy, and building inclusive, safe, resilient, and sustainable cities and communities. International policies such as the European Union's *Energy Performance of Buildings Directive* also strongly promote the development of the construction sector toward near-zero energy consumption and whole-life-cycle carbon neutrality. Against this background, improving building energy efficiency and addressing climate change have become global priorities. According to statistics from the International Energy Agency, building energy consumption accounts for approximately 40% of global total energy use, with residential buildings showing significant variations in energy consumption across different seasons and climate conditions. Particularly in summer-hot and winter-cold regions, the energy consumption problem is especially prominent, as high temperatures in summer and severe cold in winter require buildings to consume substantial energy for air conditioning and heating. Traditional building designs and materials often fail to meet the requirements for low energy consumption and environmental protection [1, 2]. Therefore, finding ways to reduce energy consumption while enhancing building comfort has become a critical issue in current architectural design. The core goal of low-carbon building design is to reduce energy consumption and carbon emissions during the operation of buildings through rational use of building materials and optimization of building facades and window structures, thereby achieving environmental sustainability [3]. In low-carbon building design, high-performance glass is an important building material. With its excellent thermal insulation, soundproofing, and light transmission properties, it has gradually become one of the key materials for improving building energy efficiency and comfort. High-performance glass can effectively reduce heat conduction and radiation, and lower building energy consumption, particularly under extreme climate conditions where its role is particularly significant. Compared to traditional glass, low-emissivity (Low-E) glass, vacuum glass, and other high-performance glass options can significantly enhance the thermal performance of building envelopes through optimized structures and materials, and effectively improve indoor environmental quality [4, 5]. At the same time, the building environment is closely related to residents' health and public well-being. The World Health Organization points out that people spend more than 80% of their time indoors. Indoor environmental quality directly affects the occupants' physical health, mental state, and work efficiency. A poor thermal comfort environment increases the risk of cardiovascular and respiratory diseases. Insufficient or uneven lighting easily leads to visual fatigue, circadian rhythm disorders, and seasonal affective disorder; glare through windows causes problems such as headaches and decreased attention [6, 7]. Therefore, optimizing the performance of building envelopes—especially window glass, which serves as the interactive interface between indoor and outdoor environments—is related to energy efficiency. It is also an important issue in the fields of built environment health and public health. However, as the application of high-performance glass in building

design increases, how to effectively balance and optimize various performance parameters remains a pressing challenge.

Currently, there are numerous studies on the application of high-performance glass in low-carbon building design. Mocerino [8] improved energy efficiency, reliability, and comfort through innovative glass technology using lean manufacturing and robotic technology while also reducing costs and increasing productivity. The focus included smart glass facades, hybrid hydrogen systems, and the integrated design and application of renewable energy. Khaleel and Bezaid [9] reviewed current glass coating technologies, and compared static and dynamic coatings, including Low-E, electrochromic, photochromic, electrochromic, gasochromic, photochromic, and thermochromic coatings. Low-E coatings have nearly reached their energy-saving limits, while photochromic coatings improve thermal performance by absorbing ultraviolet (UV) and near-infrared radiation. Dynamic coatings can adjust solar gain in response to external stimuli, though electrochromic and gasochromic coatings are relatively expensive. Tassat et al. [10] explored the potential of integrating photovoltaic technology into windows to enhance the energy generation capability, thermal performance, and lighting effects of building facades. Using genetic evolutionary optimization algorithms, they optimized the design of semi-transparent amorphous silicon photovoltaic glass. The results showed that the optimized glass increased the spatial daylight autonomy to 82%, reduced the risk of glare, significantly lowered the lighting load, and simultaneously increased the annual electricity generation. However, most current studies mainly focus on the passive energy-saving effects of glass materials. There is no systematic research on their comprehensive optimization, especially in seeking the optimal balance among energy consumption, carbon emissions, and health performance.

To address this research gap, this work proposes a multi-objective optimization method for residential building glass based on the Genetic Algorithm (GA). Taking residential window glass as the research subject, a multi-objective optimization model is constructed with the goals of reducing building operational energy consumption, decreasing lifecycle carbon emissions, and enhancing indoor health performance. A typical residential building in a summer-hot and winter-cold region (Hangzhou, China) is used as a case study for glass parameter optimization, and an optimal solution is proposed. The actual effects of glass optimization are quantified through comparisons of energy consumption, carbon emission assessments, and indoor health performance analysis before and after optimization. The innovation of this work lies in using GA to realize the multi-objective optimization of residential building glass performance. It significantly improves optimization efficiency while integrating energy consumption, carbon emissions, and health performance to form a comprehensive optimization solution. Therefore, this work hypothesizes that a GA-based multi-objective optimization approach can effectively reduce both operational energy consumption and full-life-cycle carbon emissions of residential buildings in hot-summer-cold-winter regions. These improvements are achievable while maintaining satisfactory indoor health performance standards. The main objectives include establishing a multi-objective model suitable for the performance optimization of residential building glass in hot-summer and cold-winter regions. GA is used to spin out the key performance parameters of window glass. In addition, it quantitatively analyzes the effects of the optimization solution in terms of energy consumption, carbon emissions, and indoor health performance.

Meanwhile, a promotable optimization method and technical path are provided for low-carbon and healthy building design. This work provides a reference for energy-efficient design in residential buildings in summer-hot and winter-cold regions and promotes the wider application of high-performance glass in the building industry, thereby contributing to the development of low-carbon, healthy buildings.

2 Methods

2.1 Analysis of factors affecting energy consumption and health performance in residential buildings in summer-hot and winter-cold regions

The climatic characteristics of summer-hot and winter-cold regions determine the unique needs of residential buildings in terms of energy consumption and health performance. In these regions, summers are hot and humid, while winters are cold and damp, with drastic temperature fluctuations throughout the year. This results in significant heating and cooling demands for buildings. Additionally, the high humidity in summer often leads to stuffy conditions, while the cold temperatures in winter cause discomfort. Therefore, the performance of the building envelope, heating and cooling systems, window characteristics, and indoor environmental control all have a

significant impact on both building energy consumption and occupant health.

The thermal performance of the building envelope directly affects the heating and cooling load of the building. The insulation performance of exterior walls, roofs, and floors determines the stability of indoor temperatures. Envelope structures with low thermal conductivity can reduce heat loss in winter and cooling loss in summer, thereby lowering the energy consumption of the air conditioning system [11, 12]. Moreover, the thermal mass of the exterior walls also influences the energy consumption of the building. For instance, high thermal mass walls can delay the impact of outdoor temperature fluctuations on the indoor environment, resulting in a more stable indoor temperature.

Key indicators for assessing window energy efficiency and health performance include the main window glass' thermal transmittance coefficient (K -value), solar heat gain coefficient (SHGC), and visible transmittance (VT) [13, 14]. A lower thermal transmittance coefficient reduces heat loss in winter and heat gain in summer, improving the building's energy efficiency. The SHGC influences the risk of overheating in summer and the use of solar energy in winter. Proper window parameters can improve indoor thermal comfort while reducing energy consumption. VT affects the quality of natural lighting indoors. If the VT is too low, it increases the need for artificial lighting during the day, raising energy consumption. If the VT is too high, it can cause glare issues, compromising visual comfort. Figure 1 illustrates the specific impact pathways.

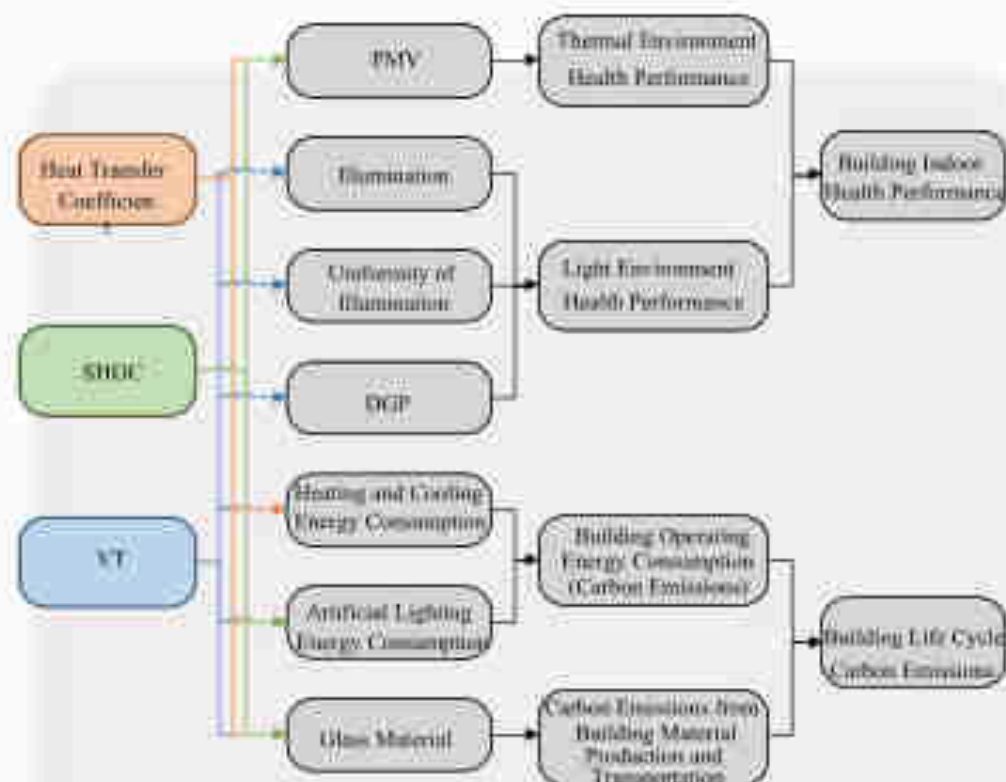


Figure 1
Impact pathways of glass performance parameters on residential building energy consumption and health performance

The proper control of indoor temperature and humidity is crucial for reducing energy consumption and enhancing occupant comfort and health [15]. In summer-hot and winter-cold regions, due to low winter temperatures, there is a high demand for heating, while the hot and humid environment in summer increases the burden on air conditioning, cooling, and dehumidification. Proper window performance, shading design, and natural ventilation strategies can effectively regulate the indoor thermal and humidity environment, reduce the load on the air conditioning system and lower building operational energy consumption. Additionally, a good indoor thermal and humidity environment can prevent the growth of mold caused by excessive humidity, reduce the likelihood of respiratory diseases among occupants, and improve health performance.

Natural lighting plays an important role in indoor environmental quality and building energy consumption. Under the premise of meeting lighting requirements, reducing the use of artificial lighting can effectively lower the operational energy consumption of the building. Well-designed windows can improve the uniformity of indoor illumination, ensuring that main activity spaces receive sufficient natural light while avoiding glare. Optimizing window parameters can ensure that the indoor lighting environment remains within a healthy range for most of the year. This can reduce the need for artificial lighting and lower electricity consumption in the building [16, 17]. Additionally, the use of natural light can improve occupants' physiological rhythms, and enhance their quality of life and health levels.

To sum up, many factors affect the energy consumption and health performance of residential buildings in both summer and cold-winter regions. These factors include building envelope, heating and cooling systems, indoor environmental control, and natural lighting. Among numerous factors, this work focuses on the analysis and optimization research of the thermal and optical properties of window glass to highlight its crucial role in enhancing building energy efficiency and creating a healthy indoor environment.

2.2 Analysis of types and technical principles of high-performance glass

High-performance glass, as one of the essential materials in modern buildings, encompasses various types and technical characteristics, primarily including Low-E glass, U-shaped glass, photovoltaic glass, and vacuum glass [18–20]. These glass materials are optimized during design and manufacturing processes to meet different functional needs, enhancing their performance in energy savings, sound insulation, and improving indoor environmental quality.

Low-E glass effectively reduces radiative heat loss by coating a Low-E film on the glass surface, thereby improving the building's insulation performance. It can reflect indoor heat, reducing energy loss in winter, while blocking heat entry in summer, achieving year-round energy-saving effects. This type of glass can also filter UV rays, protecting indoor furniture and decorations from UV damage and extending their lifespan. Additionally, Low-E glass has good light transmittance, ensuring natural lighting indoors and enhancing the comfort of living and working environments. Photovoltaic glass integrates solar cell technology, converting solar energy into electrical power. It not only serves as a decorative material for building facades

but also provides part of the building's power needs, achieving self-sufficiency and sustainable development. Photovoltaic glass, when integrated into buildings, not only reduces reliance on traditional energy sources but also decreases the building's carbon footprint, promoting the development of green buildings. With ongoing advancements in photovoltaic technology, the electricity generation efficiency and cost-effectiveness of photovoltaic glass are continually improving, making large-scale applications in buildings increasingly feasible. Vacuum glass forms a vacuum layer between two glass panels, effectively isolates heat conduction and convection, and significantly enhances the insulation performance of the glass. It has an extremely low thermal conductivity coefficient, making it one of the best insulating building glass materials available. Due to its vacuum layer which eliminates thermal losses caused by air convection, vacuum glass effectively maintains indoor warmth during winter and isolates outdoor heat during summer, significantly reducing building energy consumption. Additionally, vacuum glass offers excellent sound insulation, effectively blocking external noise and enhancing the quietness of indoor environments. U-shaped glass features an insulating layer in the center of the glass, effectively isolates external heat and noise, and enhances the building's soundproofing effects, as shown in Figure 2. This structural design not only reduces heat transfer but also lowers noise pollution inside the building, improving the living quality of occupants. U-shaped glass is widely used in the exterior wall and window designs of buildings, especially in places requiring high sound insulation and thermal insulation performance, such as airports, hospitals, and upscale residential areas.

Table 1 displays the comparison of the advantages and disadvantages of various high-performance glass types [21–23].

The application of high-performance glass in buildings not only significantly enhances the energy efficiency of the structures but also effectively improves indoor environmental quality. For example, Low-E glass reduces energy costs by controlling heat transfer, thereby decreasing heating consumption in winter and air conditioning consumption in summer. U-shaped glass and vacuum glass, with their excellent thermal insulation properties, reduce the transfer of temperatures between the interior and exterior of the building, thus improving overall insulation and enhancing the comfort of the living environment. The application of photovoltaic glass enables buildings to harness renewable energy, reduces dependence on traditional electricity sources, and enhances the building's energy self-sufficiency and environmental friendliness.

Overall, the use of high-performance glass can effectively reduce energy consumption and carbon emissions in buildings, while also

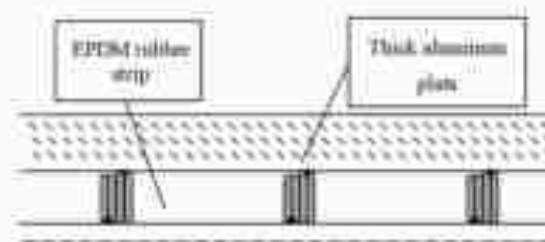


FIGURE 2
Cross-sectional diagram of U-shaped glass.

TABLE 1 Comparison of various high-performance glass types.

High-performance glass types	Application advantages	Application disadvantages	Suitable building types
Low-E Glass	Excellent thermal insulation and light transmission, significant energy-saving effect	Expensive regular cleaning and maintenance of the coating layer	Commercial office buildings, and residential buildings
U-High-strength Glass	High strength, easy construction, significant energy-saving effect	Higher initial cost, and high design requirements for glass	Large public buildings, and stadiums
Photovoltaic Glass	Provides green energy and reduces indoor lighting costs	High initial investment, technology maturity and market application need further improvement	Commercial office buildings, and residential buildings
Vacuum Glass	Best insulation performance, significant energy-saving effect	High manufacturing cost, and high installation technology requirements	High-end residential buildings, and research institutions

increasing the building's value and improving the quality of life for its occupants. A deep understanding of the different types of high-performance glass and their technical principles can better guide their rational application in buildings, driving the construction industry toward a green, low-carbon, and sustainable direction. This not only meets the current global demand for environmental protection but also provides crucial technological support for improving future urban development and human living environments.

2.3 Multi-objective optimization model based on GA

2.3.1 GA-based optimization method

To solve the complex non-linear trade-off problem between building glass performance parameters and multiple objectives (energy consumption, carbon emissions, and health performance), GA is selected as the core optimization tool. GA's strong global search capability and multi-objective optimization capability can effectively balance the complex trade-offs of building glass performance among energy consumption, carbon emissions, and health performance, improving optimization efficiency and the scientific nature of results. In addition, GA can directly generate a set of well-distributed Pareto optimal solution sets, thereby providing decision-makers with multiple performance trade-off schemes and supporting final design decisions. GA is a random optimization algorithm that simulates the natural selection process. It continuously applies operations such as

selection, crossover, and mutation in the solution space, ultimately approaching the global optimal solution [24, 25]. Here, GA is mainly employed to optimize the performance parameters of building glass while considering multiple optimization objectives, such as building operational energy consumption, lifecycle carbon emissions, and indoor health performance. The core of GA is the fitness function, which determines the "quality" of each individual in the current population, essentially evaluating how well a solution performs [26]. Here, building lifecycle carbon emissions, operational energy consumption, and indoor health performance improvements are set as optimization objectives. Therefore, a comprehensive fitness function needs to be designed to unify these objectives and transform them into either minimization or maximization forms. Specifically, the fitness function in this work is:

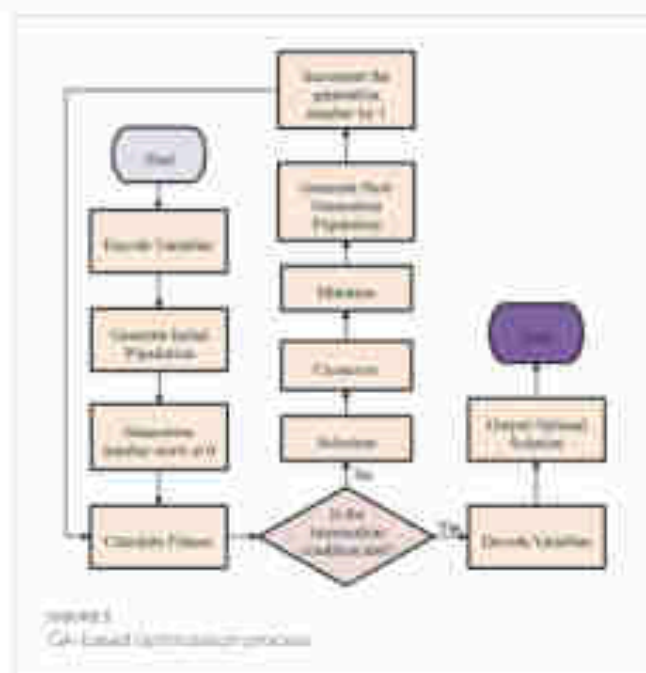
$$\max f(x) = \begin{cases} \min F_{\text{env}}(x) \\ \min F_{\text{ene}}(x) \\ \max F_{\text{hea}}(x) \end{cases} \quad (1)$$

In this context, $F_{\text{env}}(x)$ represents the calculation function for the building's lifecycle carbon emissions, which is an objective to be minimized, that is, the lower the carbon emission is, the better it is. $F_{\text{ene}}(x)$ represents the calculation function for the building's operational energy consumption, which is also a minimization objective. Optimizing the glass performance can reduce the building's energy consumption. $F_{\text{hea}}(x)$ represents the calculation function for the indoor health performance of the building, with health performance being a positive objective to maximize, that is, the healthier the indoor environment is, the better it is. Through the iterative process of the GA, the selection, crossover, and mutation operations continuously adjust the glass parameters of each individual, aiming to minimize carbon emissions and energy consumption while maximizing indoor health performance. During the optimization process, the GA evaluates each solution based on the above fitness functions, progressively seeking the optimal combination of glass performance parameters. Figure 3 illustrates this process.

Relevant studies on the application of GA in building performance optimization have been reflected in. These studies indicate that for moderately complex building optimization problems, a population size of 50–100 and 100–200 evolution generations typically achieve effective convergence. This parameter range maintains a good balance between computational efficiency and solution quality. Meanwhile, in preliminary tests, when the population size is 50 and the number of iterations is 100, the algorithm achieves a good balance between convergence speed and solution stability. Besides, the optimization results have high accuracy and ensure computational efficiency. Thus, the population size is set to 50, the number of generations is 100, the crossover rate is 0.9, and the mutation rate is 0.01.

2.3.2 Indoor health performance objectives for residential buildings

In residential buildings, optimizing indoor health performance is a key factor in affecting the health and comfort of occupants. To ensure that the building environment provides a healthy and comfortable living space for residents, this work primarily focuses on two important indoor health performance objectives.



thermal-humidity environment and lighting environment. The thermal-humidity environment refers to the impact of the combination of indoor air temperature and relative humidity on the health and comfort of residents. According to the international standard American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), indoor temperatures should be maintained between 18 °C and 26 °C; moreover, the relative humidity should remain within 30 to 70% to ensure thermal comfort and avoid the negative health effects of too high or too low humidity levels. Here, the health performance of the thermal-humidity environment is evaluated by calculating the percentage of hours that the indoor thermal-humidity environment meets health requirements, and this is used as one of the optimization objectives for GA. To quantify this indicator, the Predicted Mean Vote (PMV) standard is used as the evaluation criterion, and indoor thermal comfort is assessed hourly based on the ASHRAE standards. Then, the percentage of time during the year when the thermal-humidity environment meets health requirements is calculated. The lighting environment's health performance is also critical to the health and quality of life of occupants. According to the healthy building evaluation standards, interior spaces (such as bedrooms, studies, and living rooms) must ensure adequate natural lighting, and indoor illuminance should be maintained between 300 lx and 500 lx. The illuminance uniformity should be not less than 0.40, and the daylight glare probability (DGP) should not exceed 0.43. To quantify the lighting environment's health performance, the percentage of time that each major interior space meets the required illuminance, uniformity, and glare index under natural lighting conditions is calculated, and the total percentage of healthy lighting hours for the year is derived.

By combining the health performance objectives of the thermal-humidity and lighting environments, the goal is to maximize the percentage of healthy indoor hours throughout the year by optimizing the glass performance parameters of the windows. To this end, this work uses the comprehensive healthy hours percentage (H) as the

objective function for optimization, as shown in the following equation:

$$H = \alpha_1 \cdot H_{th} + \alpha_2 \cdot H_{lg} \quad (2)$$

$$H_{lg} = \frac{H_L + H_U + H_{DGP}}{3} \quad (3)$$

Here, H_{th} represents the percentage of healthy hours for the thermal-humidity environment, and H_{lg} represents the percentage of healthy hours for the lighting environment. α_1 and α_2 are the weights for the thermal-humidity and lighting environments, respectively, with values of 7/12 and 5/12. H_L , H_U , and H_{DGP} represent the annual indoor illuminance, illuminance uniformity, and DGP healthy hours percentage, indicating the proportion of time during the year when indoor illuminance, illuminance uniformity, and DGP meet health requirements. The core of this optimization objective is to maximize the percentage of healthy hours for both indoor thermal-humidity and lighting environments by optimizing glass performance, thereby enhancing the health and comfort of the occupants.

2.3.3 Operational energy consumption objective

In building design and optimization, operational energy consumption is a key indicator for assessing building energy efficiency and environmental impact. The energy consumption of a building mainly comes from the air conditioning, heating, and lighting systems, and the energy usage of these systems is closely related to indoor thermal-humidity conditions and the quality of the lighting environment. Here, the operational energy consumption objective of buildings focuses on the electricity consumption of air conditioning, heating, and artificial lighting systems, aiming to reduce overall energy consumption through the optimization of glass performance and building design. The thermal-humidity environment indoors has a significant impact on the energy consumption of the air conditioning and heating systems. To maintain a comfortable indoor thermal-humidity environment, the air conditioning and heating systems need to adjust according to external climate changes, especially during extreme seasonal conditions, where system load is high, leading to increased energy consumption. Therefore, the energy consumption of the air conditioning and heating system is considered one of the key indicators for evaluating the building's operational energy efficiency in the optimization model. When natural lighting is insufficient, the artificial lighting system is activated to ensure that indoor illuminance meets health requirements. According to worldwide relevant building design standards, the indoor health illuminance requirement for residential buildings is 300–500 lx. When lighting conditions fall below 300 lx, the artificial lighting system will turn on to supplement the lighting. Thus, the energy consumption of the lighting system is also an important component of the building's total energy consumption. To quantify the building's operational energy consumption, the total electricity consumption per unit area is set as the optimization objective, as shown in the following equation:

$$E = E_{th} + E_{lg} \quad (4)$$

Here, E represents the total operational energy consumption of the building, indicating the total energy consumption per unit area of the building over the course of 1 year. E_{th} is the energy

consumption of the air conditioning and heating system, and E_{light} is the energy consumption of the lighting system. The units for all three energy consumptions are kilowatt-hours per square meter per year ($\text{kWh}/(\text{m}^2 \cdot \text{a})$). The optimization objective is to enhance the quality of the indoor thermal-humidity environment and lighting environment by improving the window glass performance. This is intended to reduce the energy consumption of the air conditioning, heating, and lighting systems, and ultimately lower the building's overall operational energy consumption. In this process, the optimization plan must not only consider energy-saving effects but also balance the comfort and health of the indoor environment.

2.3.4 Carbon emission objective

The carbon emissions over the entire life cycle of a building are one of the key indicators for assessing its environmental impact. This work analyzes the carbon emissions throughout the building's life cycle and explores the impact of different window technology parameters on carbon emissions. The carbon emissions over the entire life cycle of a building mainly consist of three stages: the material production and transportation stage, the construction and demolition stage, and the operational stage.

During the building's material production and transportation stage, the production and transportation of glass involve multiple steps, each generating a certain amount of carbon emissions. It should be noted that this work mainly focuses on the environmental dimension in life cycle assessment. As a result, it focuses on quantifying carbon emissions at each stage as an environmental endpoint indicator. The embodied carbon generated in the material production stage has been taken into account in the calculation, which, to a certain extent, reflects the environmental cost brought by the initial investment in high-performance glass. Although economic cost (i.e., initial investment) is an important factor in engineering decision-making, this work focuses on establishing an optimization model for environmental performance. Therefore, economic parameters are not included in the objective function. The carbon emissions from the glass production and transportation stage are calculated using the following equation:

$$C_{\text{GT}} = C_{\text{G}} + C_{\text{T}} \quad (5)$$

C_{GT} represents the carbon emissions during the glass production and transportation phase, measured in kilograms of carbon dioxide equivalent per square meter ($\text{kgCO}_2\text{e}/\text{m}^2$). C_{G} refers to the carbon emissions during the glass production phase, and C_{T} represents the carbon emissions during the glass transportation phase, measured in kgCO_2e .

The carbon emissions from the construction and demolition phases typically account for a smaller portion of the building's total life-cycle carbon emissions, so this work assumes them to be negligible (set to 0).

The operational phase of the building mainly includes the power consumption of the heating, ventilation, and air conditioning (HVAC) system and the lighting system. During this phase, electricity is the primary energy source, and the building's carbon emissions are mainly related to the carbon emission factor of the power grid and the building's energy consumption level. The carbon emissions during the

operational phase of the building are calculated using the following equation:

$$C_{\text{EX}} = \frac{(E_{\text{HVAC}} + E_{\text{light}}) \times E_{\text{EF}} \times \gamma}{A} \quad (6)$$

C_{EX} represents the carbon emissions during the building's operational phase, measured in $\text{kgCO}_2\text{e}/\text{m}^2$. E_{HVAC} is the annual electricity consumption of the building's HVAC system, E_{light} is the annual electricity consumption of the building's lighting system, measured in kilowatt-hours per year (kWh/a). E_{EF} is the average CO_2 emission factor of the regional power grid in China, γ is the building's design life, measured in years, and A is the building's floor area, measured in m^2 .

The carbon emission optimization objective is to reduce the unit area carbon emissions of the building throughout its entire life cycle by optimizing the window parameters. While achieving the optimal thermal-humidity environment and lighting environment for the building, this also further reduces the building's carbon footprint. Reasonable design and optimization of window technical parameters can reduce the building's energy consumption and decrease carbon emissions during the material production, transportation, and operational phases. This can achieve the goal of green and low-carbon buildings while maintaining the building's functionality and comfort.

2.3.5 Feasibility constraints of glass performance parameters

During GA-based multi-objective optimization, treating glass thermal and optical parameters—such as K -value, SHGC, and VT—as entirely independent variables may produce theoretically optimal configurations. However, such solutions could prove physically unsustainable or commercially unavailable in practice. Explicit feasibility constraints are introduced into the optimization model to ensure the physical rationality and engineering practicality of optimization results. These constraints are mainly based on the physical principles of high-performance glass and commercial product databases.

Specifically, there is an inherent physical correlation between SHGC and VT, as both are jointly affected by the coating properties of the glass surface, the number of layers, and the intermediate gas medium. Generally, for glass with similar coating types, higher VT is usually accompanied by higher SHGC. To quantify this relationship, regression analysis is performed on the SHGC and VT of 1,075 glass samples from the database. The analysis references both the ASHRAE Handbook—Fundamentals and product databases from major glass manufacturers such as Saint-Gobain and AGC. This leads to the establishment of a feasible region boundary constraint as shown in Equation 7.

$$0.8 \leq VT \leq 0.15 + 5 \cdot SHGC \leq 1.2 \leq VT \leq 0.1 \quad (7)$$

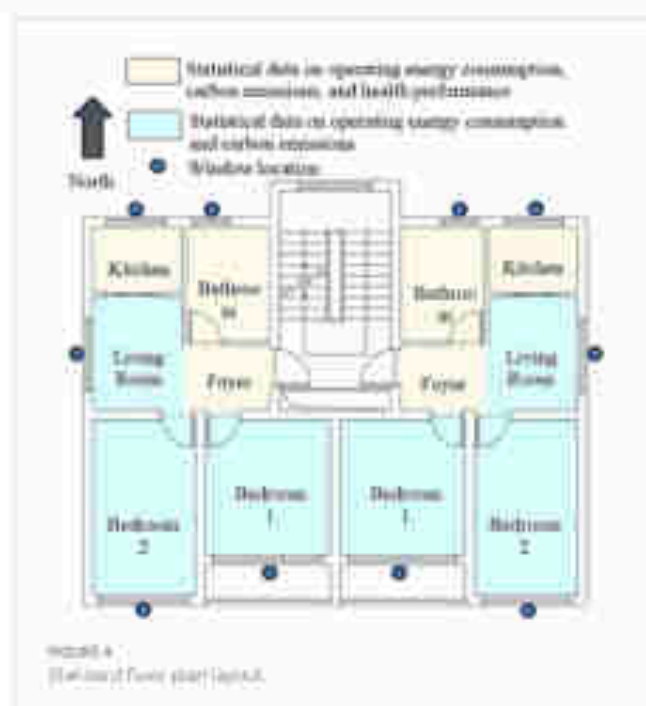
This constraint ensures that when the optimization algorithm searches the solution space, it numerically includes design schemes where the combinations of SHGC and VT values have physical laws. In addition, the K -value of glass is closely related to the number and thickness of its insulating layers, as well as the filled gas (such as air and argon). A lower (better) K -value usually requires a more complex insulating layer structure or the use of low-conductivity gas, which

may have a negative impact on VT to a certain extent. In the work, the generation of the initial population of optimization variables and iterative mutation operations is strictly restricted within the scope of the commercial glass product parameter database. This means that every combination of glass performance parameters generated by the algorithm during the "selection," "crossover," and "mutation" operations corresponds to an actually existing glass product or one that can be manufactured using existing technologies.

By introducing the above-mentioned physical correlation constraints and commercial product database screening, the multi-objective optimization model can effectively limit the search space to a "feasible solution" region. This ensures that all Pareto optimal solutions have engineering feasibility and enhances the practical value and guiding significance of the optimization results.

2.4 Case selection and data collection

This work selects a typical residential building located in the hot-summer and cold-winter region of Hangzhou as the research object. A three-dimensional model of the building is created in Rhinoceros software for subsequent building performance simulation and optimization analysis. The building has six floors, with a form factor of 0.39 for the above-ground portion. It does not have an elevator, and the overall layout is compact with reasonable functional zoning. The standard floor layout adopts a mirrored design of two east-west units, with each floor covering an area of 120 m², ensuring good residential comfort and space utilization. The building's interior space includes two bedrooms, a living room, a kitchen, and a bathroom, covering the main functional areas of a typical residence. The building's exterior windows are configured with double-glazed insulated glass consisting of 6 mm Low-E glass, 12 mm air gap, and 6 mm transparent glass. Figure 4 shows the floor plan of the building.



For accurate building performance simulation, detailed indoor environment parameters are set in the work as the basis for energy simulation and health performance evaluation. Indoor thermal disturbance settings include occupants, lighting, and equipment. The occupant schedule is set according to typical residential routines: 2 people are set for weekday nights (23:00 to 7:00 the next day), 1 for weekday days (7:00 to 18:00), and 2 for weekday evenings (18:00 to 23:00), on weekends, 2 people are set to be present for most of the day. The occupant's metabolic rate takes the typical value of 1.0 met under resting conditions. Clothing thermal resistance is adjusted according to the season: 0.5 clo in summer and 1.0 clo in winter, to reflect actual dressing habits. The set temperature for heating is 20 °C, and the set temperature for cooling is 26 °C, the system operation time is synchronized with the occupant presence time. The lighting power density is set to 9 W/m², and the equipment power density is set to 4 W/m²; their operation schedules are related to occupant activities.

The collected data includes the window unit, specifically the glass, with parameters such as the thermal transmittance (K-value), SHGC, and VT, which directly relate to the building's energy efficiency and further influence the building's carbon emissions. The thermal transmittance of the glass determines the efficiency of heat transfer through the window. A higher K-value means that the window will result in more heat loss during winter, increasing the energy consumption and carbon emissions of the HVAC system. SHGC, on the other hand, directly affects the window's absorption of solar radiation heat, thereby influencing the indoor thermal environment. A higher SHGC can lead to overheating, increasing the load on the air conditioning system. In the simulation, the calculation of mean radiant temperature fully considers the temperature of each indoor surface. Among them, the inner surface temperature of the glass is obtained through dynamic heat balance calculation based on its K-value, the indoor-outdoor temperature difference, and solar radiation heat gain (comprehensively considering SHGC and incident angle correction). This ensures the accuracy of the radiant temperature component in the PMV evaluation index.

To ensure the scientific accuracy and reliability of the data, a residential building glass parameter database is established. This database is based on the ASHRAE Handbook Fundamentals, the Zhejiang Province Residential Building Energy Efficiency Design Standard DB33/1013-2013, and related engineering practices. It includes 1,075 different types of glass, with each entry containing four key parameters: average thermal transmittance, SHGC, VT, and embodied carbon emissions, providing detailed data support for subsequent research. From the perspective of reducing the types of components in the actual project, the simulation sets the windows on the same facade to be identical. It means the performance parameters of the glass in each window component on the same facade are the same. In the simulation, glass performance parameters are input based on the database.

3 Results and discussion

3.1 Analysis of the results for glass performance parameter optimization

Based on the building performance optimization with meteorological parameters from Hangzhou, the initial building

TABLE 2 Initial building performance parameters.

Parameter Name	Result	Sub-parameter name	Result
Operating Energy			
Consumption (kWh/m ² /yr)	19.95		
Carbon Emission (kgCO ₂ /m ² /yr)	2023.29		
Indoor Health Time Proportion (%)	34.38	PMV	12.87%
		Wetbulb	11.74%
		Humidity	50.73%
		Clear	44.04%

performance parameters are obtained from the simulation, as shown in Table 2.

After the GA calculation, a total of 55 Pareto optimal solutions are obtained. Figure 5 shows the mean and standard deviation (SD) of the solutions to glass performance parameter optimization for different orientations.

Figure 5 reveals that there are certain differences in the glass thermal transmittance, SHGC, and VT for the four orientations: East, South, West, and North. The average thermal transmittance for the East-facing windows is 1.29, SHGC is 0.48, and VT is 0.52, with standard deviations of 0.19, 0.034, and 0.066, respectively, indicating significant performance fluctuations for the East-facing windows. The glass performance for the South-facing windows is relatively stable, with an average thermal transmittance of 1.18, SHGC of 0.46, and VT of 0.54. The optimization results for the West-facing windows show a lower thermal transmittance (1.63) and SHGC (0.36). The optimization results for the North-facing windows show the lowest thermal transmittance, at 1.14. Overall, the optimization results for South-facing windows are more stable and perform better, while the optimization results for East and West-facing windows fluctuate more. The optimization parameters for the North-facing windows are the least favorable, with a significantly lower thermal transmittance, which impacts the building's energy efficiency.

Figure 6 shows the mean performance parameters of the window glass in the Pareto optimal solutions.

According to Figure 6, the glass performance parameters for the four orientations show significant differences, reflecting the impact of windows facing different directions on building energy efficiency and indoor environment. In terms of thermal transmittance, the optimization result for South-facing windows is the best, with an average value of 1.042, noticeably higher than the other orientations. The average thermal transmittance for East-facing windows is 1.779, slightly lower than South-facing windows, but still higher than West and North-facing windows. This suggests that South-facing windows offer better thermal performance, reducing heat loss during winter. Regarding SHGC, South-facing windows have a value of 0.459, slightly higher than the other orientations, indicating that South-facing windows can more effectively utilize solar radiation heat to improve winter energy efficiency. On the other hand, North-facing windows are the least favorable for heat absorption. For VT, South-facing windows have a value of 0.538, which is relatively high, meaning they provide better natural daylighting. Overall, South-facing windows

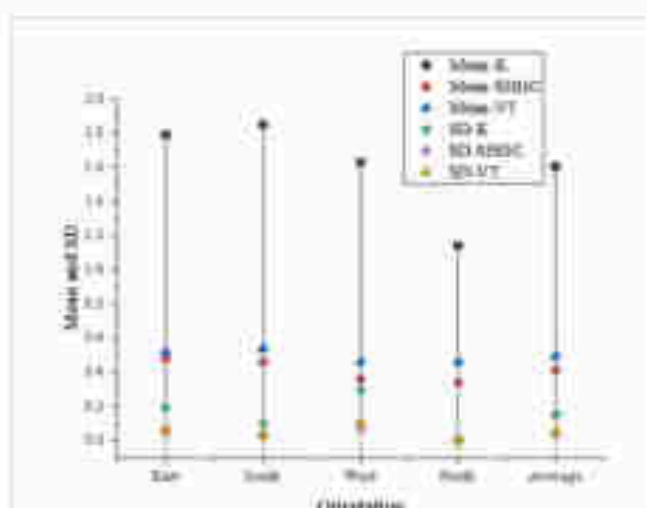


FIGURE 5 Optimization results of glass performance parameters.

perform well in terms of thermal performance, solar heat gain, and natural daylighting, making them suitable for optimization design.

In summary, for residential buildings in summer-hot and winter-cold regions, optimizing glass performance parameters is not only related to the building's energy efficiency and carbon emissions but also directly impacts the indoor health environment. From the GA optimization results, it is clear that South-facing windows stand out in the overall optimization. Their higher SHGC and VT contribute to improving winter energy efficiency and natural daylighting, and effectively reducing heating energy consumption and carbon emissions. Additionally, South-facing windows perform better in terms of thermal-humidity and lighting environments, enhancing indoor comfort and health. Therefore, for building designs in summer-hot and winter-cold regions, when optimizing the glass performance, it is recommended to prioritize the optimization of South-facing windows. A higher thermal transmittance and appropriate SHGC can be adopted to improve building energy efficiency and reduce carbon emissions. For East and West-facing windows, appropriate adjustments should be made based on specific conditions, especially in areas with higher heat load, where SHGC can be reduced to mitigate the risk of overheating in summer. Furthermore, the lower thermal performance and light conditions of North-facing windows indicate that measures, such as optimizing window materials or adding daylighting devices, may be required to compensate for their shortcomings, ensuring the building's energy efficiency and indoor health throughout the year. In summary, when optimizing glass performance parameters, in addition to reducing energy consumption and carbon emissions, the improvement of the indoor health environment should be fully considered. In particular, thermal-humidity and lighting environments should be considered to achieve a comprehensive, multi-objective optimization.

3.2 Comparison of building operational performance before and after optimization

Among all the Pareto optimal solutions, five glass optimization schemes that best align with the actual project in Hangzhou based on a typical building were selected, as shown in Table 3.

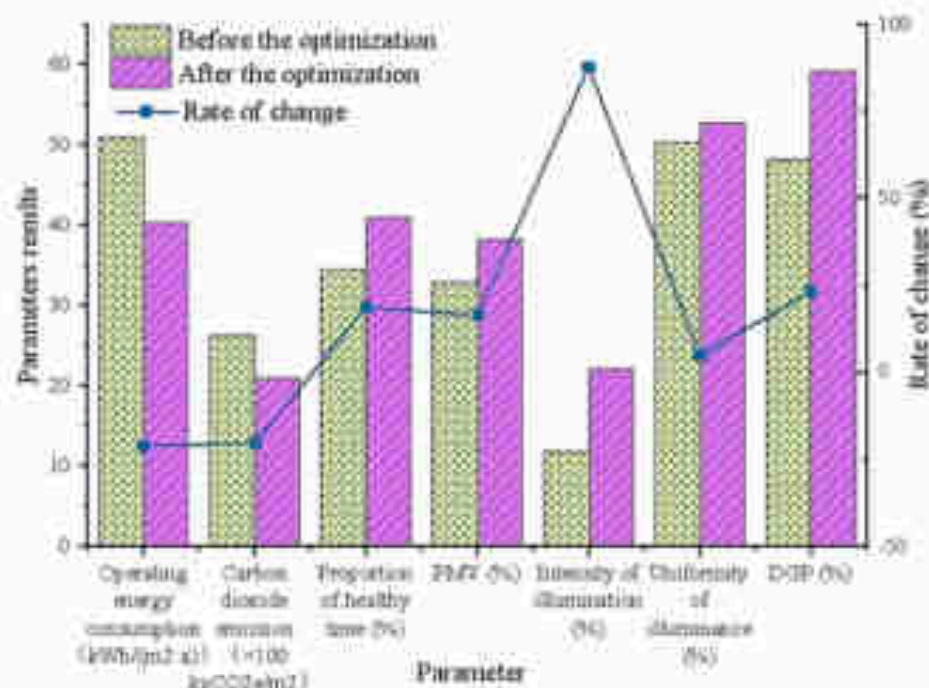


Figure 7
Comparison of light performance (data application)

Figure 7 shows the results of operational energy consumption, carbon emissions, and the proportion of healthy time before and after using the optimization schemes. The post-optimization results are presented in orange.

Figure 7 shows that the optimized window glass performance significantly improves the building's operational energy efficiency, reduces carbon emissions, and enhances the indoor health environment. First, the optimized building's energy consumption decreases from 50.95 kWh/(m²·a) to 40.26 kWh/(m²·a), reducing energy consumption by 20.98%, indicating that the optimization scheme effectively improves the building's energy efficiency. Besides, carbon emissions are also significantly reduced, from 2.623 kgCO₂/m² to 2.003 kgCO₂/m², a decrease of 23.97%, further proving the positive environmental impact of the optimization scheme. In terms of health performance, the proportion of healthy indoor time increases from 34.46 to 40.9%, an increase of 18.69%. This suggests that the optimized glass parameters significantly improve the thermal-humidity and light environments, and enhance the comfort of the occupants. Specifically, the PMV ratio increases by 16.31%, and the uniformity of illuminance also improves, particularly in the enhancements in illuminance intensity and DGP, demonstrating the optimization scheme's effectiveness in enhancing natural daylighting and reducing glare.

In summary, the window glass performance optimized through GA shows significant improvements in multiple aspects. The optimization scheme not only effectively improves the building's operational energy efficiency and reduces carbon emissions but also significantly enhances the indoor health environment, especially in optimizing the thermal-humidity and light conditions. The optimized glass design improves indoor thermal comfort, illuminance

uniformity, illuminance intensity, and DGP, thereby enhancing the comfort and health experience of the occupants. Furthermore, the optimization scheme adjusts windows for different orientations. In particular, south-facing windows fully utilize solar radiation heat and natural daylighting, which effectively reduces the building's air conditioning and heating energy consumption, thus further lowering carbon emissions. In building design for summer-hot and winter-cold regions, prioritizing the optimization of south-facing windows maximizes the building's energy efficiency and indoor comfort. For East, South, and West-facing windows, adjustments should be made based on varying heat load demands; optimized designs can mitigate the risk of overheating in summer and further enhance the building's overall energy efficiency. Overall, the proposed glass performance optimization scheme provides strong support for multi-objective optimization of building energy efficiency, carbon emissions, and indoor health performance, offering practical guidance for low-carbon building design.

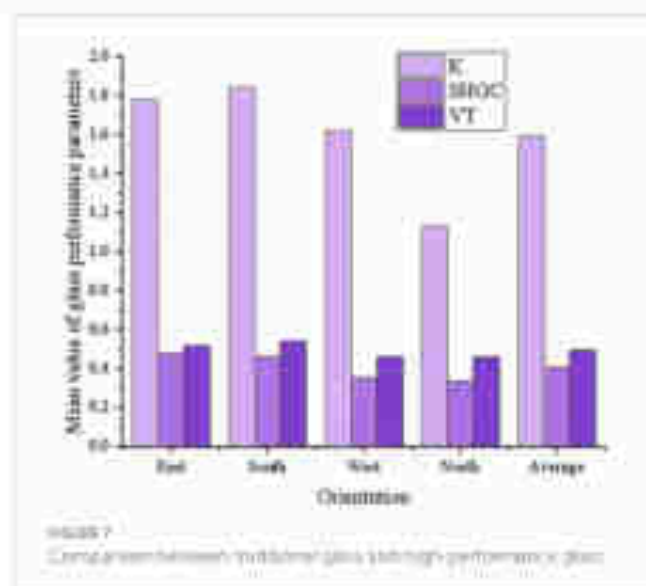
4 Discussion

Through GA optimization, this work obtains glass performance parameter combinations that balance energy consumption, carbon emissions, and health performance. The optimization results show that windows with different orientations have systematic differences in their requirements for glass performance parameters, which reflects the different climatic driving forces faced by external building windows. Compared with the study by Wang et al. (27), this work also adopts a multi-objective optimization method. However, their study mainly focused on improving light transmittance through the

TABLE 2: Typical residential glass optimization schemes for Hangzhou region.

Scheme	Scheme	South	West	North
Scheme 1	$3 + 5A + 3Low-E$	$3 + (3A) + 3Low-E$	$3 + 5A + 6Low-E$	$6Low-E + (3A) + 3 + (3A) + 3$
Scheme 2	$6 + 15A + 6Low-E$	$3 + (3A) + 3Low-E$	$6 + 5A + 6Low-E$	$6Low-E + (3A) + 3 + (3A) + 3$
Scheme 3	$3 + 5A + 3Low-E$	$6 + (3A) + 6Low-E$	$6 + 5A + 6Low-E$	$6Low-E + (3A) + 3 + (3A) + 3$
Scheme 4	$3 + 15A + 3Low-E$	$6 + (3A) + 6Low-E$	$6 + 5A + 6Low-E$	$6Low-E + (3A) + 3 + (3A) + 3$
Scheme 5	$3 + (3A) + 3Low-E$	$3 + 5A + 3Low-E$	$6 + 5A + 6Low-E$	$6Low-E + (3A) + 3 + (3A) + 3$

A denotes clear glass and 3A denotes the argon gas layer. All numbers must be with "mm". For example, "3 + 5A + 3Low-E" indicates the window glass composition is 3 mm regular glass + 5 mm argon gas + 3 mm Low-E glass.



thin-film interference principle of multi-layer thermochromic smart windows to balance energy consumption, anti-glare, and daylighting. In contrast, this work uses GA to integrate energy consumption, carbon emissions, and health performance simultaneously within a broader scope, proposes a comprehensive optimization framework. Meanwhile, targeted optimization is conducted for windows with different orientations—demonstrating the method's universality and adaptability. Shakk et al. (28) addressed the energy consumption issue of glass buildings by developing three double-glazed systems with organic phase change materials (21/30/33 °C). This system could save operating costs while maintaining sufficient natural daylighting. However, this work optimizes material parameters and comprehensively considers building operating energy consumption and life-cycle carbon emissions; it also introduces health performance as an optimization objective, forming a more comprehensive multi-objective optimization system. Volf et al. (29) conducted a field experiment in 22 apartments to compare the impact of double-layer high-light transmittance glass and triple-layer low-energy glass on residents' health. They found that although high-light transmittance glass saved 11.0% energy and was rich in circadian rhythm spectrum, users of low-energy glass reported fewer sleep difficulties and higher daylight satisfaction. This reveals the complex relationship that building glass selection needs to balance energy efficiency and health effects. Although this work is based on simulation optimization, through multi-objective GA, it can achieve an adjustable balance

between different performance objectives and provide specific parameters applicable to practical design. It provides theoretical guidance and an optimization framework for similar field studies, with strong promotion potential. In conclusion, this work incorporates energy consumption, carbon emissions, and health performance into optimization objectives simultaneously and considers the different needs of windows with different orientations. Compared with existing studies, the method of this work is more systematic and scalable. It provides a scientific basis for high-performance glass design while offering a feasible technical path for low-carbon and healthy building design. This has important theoretical value and practical significance for achieving building energy conservation, carbon emission reduction, and improving the residential health environment.

It is worth noting that the optimization model of this work does not directly simulate the spectral characteristics of glass; however, its optimization results—seeking the optimal combination between lower SHGC and higher VT—are essentially highly consistent with the design concept of high-performance spectrally selective glass. By applying a special functional coating on its surface, spectrally selective glass can selectively transmit the visible light band to ensure natural daylighting and vision. Meanwhile, it can effectively reflect or absorb the near-infrared band in solar radiation to reduce unnecessary solar heat gain. This spectral regulation capability allows it to break the positive correlation usually presented by SHGC and VT parameters in traditional glass. Thus, a practical and feasible technical solution can be provided for realizing the parameter optimization path advocated by this work. For example, the optimization results suggest that south-facing windows adopt a relatively higher SHGC to facilitate passive heat gain in winter, while maintaining a higher VT to ensure daylighting. This parameter combination is exactly a typical feature of spectrally selective Low-E glass. Its coating design allows a large amount of visible light to pass through but has a high reflectivity for near-infrared radiation. Thus, this allows more solar radiation heat to enter the room in winter while maintaining excellent daylighting performance throughout the year. For east and west-facing windows, the optimization results show a lower SHGC requirement to resist the severe summer overheating risk caused by low-angle sunlight. At this time, dynamic glass with stronger solar radiation regulation capability or spectrally selective glass with a lower shading coefficient may be ideal carriers for achieving this optimization goal. The simulation of this work is based on comprehensive SHGC and VT parameters and does not deeply decompose spectral details. However, previous studies have confirmed that different bands in short-wave solar radiation have

different impacts on building thermal comfort, and near-infrared radiation is the main factor causing an increase in human thermal sensation. Therefore, using spectrally selective glass, by filtering near-infrared radiation, can generate a lower radiant heat load than ordinary glass under the premise of maintaining the same illuminance level. Thus, it can improve the health performance of the indoor thermal and humid environment at a deeper level.

In conclusion, the multi-objective optimization results of this work demonstrate the great potential and advantageous directions of applying spectrally selective glass in hot-summer and cold-winter regions from the perspective of building performance requirements. Future research could utilize the spectral transmittance curve of glass as a more precise optimization variable. This approach would enable more direct coupling between material optical properties and overall building environmental performance during the design stage. This provides more precise guidance for promoting the design of next-generation high-performance building envelopes.

5 Conclusion

Through the GA-based multi-objective optimization study of residential building glass in summer-hot and winter-cold regions, this work reaches the following conclusions: (1) In the hot-summer and cold-winter climate conditions of Hangzhou, the optimization of window glass can significantly improve building energy efficiency and reduce carbon emissions. The optimized glass thermal transmittance, SHGC, and VT all show considerable improvements, particularly for South-facing windows, where the optimizations of thermal transmittance and SHGC is most significant. This indicates that South-facing windows have better thermal performance and solar radiation heat utilization efficiency. (2) The optimization scheme effectively reduces the building's operational energy consumption and carbon emissions. The optimized building's operational energy consumption decreases from 90.95 kWh/(m²·a) to 40.26 kWh/(m²·a), a reduction of 20.98%; carbon emissions also drop from 2.623 kgCO₂e/m² to 2.083 kgCO₂e/m², a reduction of 20.57%, fully verifying the improvement of building energy efficiency and environmental benefits from the optimization scheme. (3) In terms of improving indoor health performance, the optimized window glass effectively enhances the indoor thermal-humidity and light environment. The proportion of healthy indoor time increases from 34.46 to 40.0%, particularly excelling in illuminance uniformity, illuminance intensity, and glare reduction, improving the comfort of the occupants. This means that the time residents spend in thermally and visually comfortable environments throughout the year is substantially extended. This goes beyond the scope of traditional building energy conservation and provides quantifiable technical paths and case support for proactively promoting public health through architectural design. In summary, the findings demonstrate that optimizing glass performance parameters can effectively improve building energy efficiency and environmental benefits while also enhancing the health environment for residents. It can achieve multi-objective optimization in terms of energy efficiency, carbon emissions, and health performance. Therefore, it is recommended that, in building design for summer-hot and winter-cold regions, South-facing windows be prioritized, and reasonable glass performance optimization be applied according to the characteristics

of windows in different orientations to achieve comprehensive optimization in building design. This work provides a scientific basis for architects to design residential buildings in hot-summer and cold-winter regions. It suggests that priority should be given to optimizing the glass performance of south-facing windows during the design process to improve energy efficiency and health performance. At the same time, policymakers can incorporate relevant optimization standards into building energy conservation codes to promote the popularization and application of high-performance glass and advance the development of low-carbon buildings and healthy cities.

Although this work has achieved significant results in optimizing window glass performance for residential buildings in summer-hot and winter-cold regions, there are still certain limitations. First, the work primarily focuses on the climate conditions in Hangzhou and has not explored the adaptability to other regions. Hence, future research could expand to optimization schemes for different climate zones and building types to verify their universality and adaptability. The 18.69% increase in the proportion of healthy time is a value based on simulation results and has not undergone statistical significance testing. The result reflects the predicted trend under the set model parameters and environmental conditions. In subsequent studies, more measured data can be used for verification to enhance the reliability of the conclusions. Moreover, the optimization results are based on short-term simulations and lack long-term field tracking data, so the impact of glass performance optimization on long-term building operations has not been fully reflected. Future research could further improve the optimization model through long-term monitoring data and actual building feedback, and evaluate its long-term benefits. In addition, this work does not fully consider the interactive effects of building structure, interior layout, and other factors on the glass optimization results. Future studies could conduct multi-dimensional optimization research in more complex building environments. Through these further studies, more comprehensive and in-depth technical support could be provided for low-carbon buildings and healthy city planning. Specifically, future research can conduct 12–24 months of monitoring in several representative residential units. Data, such as indoor and outdoor temperature and humidity, illuminance, CO₂ concentration, sub-item energy consumption of air conditioners and lighting, and glass surface temperature, are collected. Bayesian calibration and data assimilation methods regularly update the simulation model. These methods quantify the long-term energy efficiency, health benefits, and life-cycle carbon emission changes of glass optimization in different seasons and operating conditions. Future research could enhance the applicability and robustness of conclusions by incorporating additional variables into the optimization decision space. These may include building geometry parameters like window-to-wall ratio and orientation, envelope heat capacity, internal heat loads, shading and ventilation strategies, HVAC performance characteristics, and usage behavior patterns. First, key factors are screened through global sensitivity analysis. Then, multi-objective GA combined with surrogate models such as Kriging-polynomial chaos and multi-fidelity simulation is used to conduct multi-dimensional optimization and robustness analysis. Finally, the Pareto fronts under different climate zones are compared to provide cross-climate design recommendations. At the same time, a life-cycle cost model covering initial investment, operation and maintenance, and potential health benefits is constructed. Meanwhile, this model is integrated with the optimization

framework with economic objectives to evaluate the economic feasibility of different optimization schemes.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YH: Writing – review & editing, Software, Methodology, Conceptualization, Project administration, XF: Supervision, Resources, Writing – original draft, Data curation, JL: Formal analysis, Writing – original draft, JG: Visualization, Validation, Writing – original draft.

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References

- Yamadaoguerici, S., Yekhele, S., and Andersson, A. Optimizing building energy consumption in office buildings: a review of building retrofits and control systems and factors influencing energy savings. *J. Build. Eng.* (2023) 56, 107235. doi: 10.1016/j.jbe.2023.107235
- Bom, T., Hoffmann, H., Ockers, C., and Thoma, H. Applied single and hybrid active energy techniques for building energy consumption and thermal comfort: a comprehensive review. *Solar Energy* (2023) 256, 189–228. doi: 10.1016/j.solener.2023.05.088
- Li, X., Li, S., Ma, X., Li, B., Zhang, X., Wang, B., et al. A review on the policy, technology and evaluation method of low carbon buildings and communities. *Energy* (2023) 16, 1773. doi: 10.1016/j.energy.2023.117733
- Lee, Y. J., Kim, S.-H., Heo, J.-H., and Lee, B.-H. Optimizing window glass design for energy efficiency in south Korean office buildings: a hierarchical analysis using energy simulation. *Buildings* (2020) 10, 2004. doi: 10.3390/buildings10122004
- Li, X., and Wu, Y. A review of computer window glazing systems for building energy saving and daylight control: glazing technologies and their building performance prediction. *J. Build. Phys.* (2023) 46, 496–540. doi: 10.1177/1744259123118914
- Carlsen, D.G., Remington, M.F., Kikemulak, D., Macken, A.A., Wernat, D., Cornspon, G., et al. Evaluating circadian light exposure, methodology and health implications. *Res. Phys. Med.* (2020) 13, 4015. doi: 10.1027/rosm.2020.0415
- Ho, C., Zhang, W., and Gao, Y. The impact of building windows on occupant well-being: a review integrating visual and non-visual pathways with multi-objective optimization. *Buildings* (2023) 13, 2577. doi: 10.3390/buildings13122577
- Mosmann, G. High performance and intelligence of glass technologies in architecture. *J. Arch. Eng. Constr.* (2020) 14, 199–206. doi: 10.17365/1934-7688/2020.04.005
- Khalil, K., and Benoit, D. Climate and human cooling technologies for architectural glazing applications. *Energy Buildings* (2023) 284, 1. doi: 10.1016/j.enbuild.2023.111022
- Wang, A., Karampanos, T., Kornhuber, H., and Arns, E.D. Multi-objective evolutionary optimization of photovoltaic glass for thermal, daylight, and energy considerations. *Solar Energy* (2023) 264, 11. doi: 10.1016/j.solener.2023.110270
- Li, X., Li, X., and Guo, Z. Impact of building envelope design parameters on thermal building anthropogenic load reduction. *Build. Environ.* (2023) 234, 110734. doi: 10.1016/j.buildenv.2023.110734
- Gupta, V., and Deb, G. Envelope design for low-energy buildings in the tropics: a review. *Renew. Sustain. Energy Rev.* (2023) 186, 113658. doi: 10.1016/j.rser.2023.113658

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- Chenari, M., and Schneider, S. Solar window transmittance: reflecting building performance through advanced technologies. *Energy* (2020) 17, 3369. doi: 10.3390/en17133369
- Maqsood, M.T. Assessing glass configurations for energy efficiency in building envelopes: a comparative. *J. Appl. Sci. Eng.* (2024) 28, 319–33. doi: 10.47807/jae.202302.280210115
- Zakaria, S., Hengue, J., Georges, J., Benabden, A., and Boudou, Y. A method for assessing indoor climate suitability for improving comfort, consistency and quality of life. *Arxiv* (2023) 18, 313. doi: 10.25907/2023.03.03.010
- Aladidi, M.D., Ghazali, H., and Sanyal, H. Multi-objective optimization of window and shading systems for enhanced office building performance: a case study in Qatar. *Iran. J. Electr. Eng.* (2023) 12, 91–110. doi: 10.1007/s11337-023-00235-8
- Zachari, G., Hoesen, M., and Tranahy, G. Exploring the synergy of advanced lighting controls, building information modeling and internet of things for sustainable and energy-efficient buildings: a systematic literature review. *Sustainability* (2024) 16, 1055. doi: 10.3390/su16121055
- Ahmed, J., González-Lázaro, M.A., Aladidi, M., Ben Kadda, M., Deydalla, A.T., and El-Sharaby, M.A. Glass fibre reinforced concrete: overview on mechanical, durability and microstructure analysis. *Materials* (2022) 15, 11. doi: 10.3390/ma15113111
- Blay, J., Blay, J., and Thibaut, L. Glass fibre reinforced concrete as a durable and advanced material for structural and architectural elements in urban city: a review. *Materials* (2022) 15, 11. doi: 10.3390/ma15082514
- Sarraf, B.G., Sarraf, M., and Elan, A. Manufacturing of a novel thermoplastic hybrid reinforced polymer composite (FSG/VE) for high thermal strength as optimization approach for FSG/VE. *Appl. Polym. Symp.* (2023) 119, 2077–84. doi: 10.1002/app.5114877-2
- Opheer, V.L., Popescu, A.P., Popescu, D.M., and Alotaibi, M.I. A review on corrosion, mechanical, and chemical properties of glass fibre reinforced epoxy composites for high-voltage insulator core and applications: challenges and recommendations. *Polym. Bull.* (2022) 75, 607–64. doi: 10.1007/s00289-022-03446-z
- Omari, M., and Nouri, E. Effect of GFRP tubes and polypropylene fibres on flexural strength in high-performance concrete beams with glass powder and microsilica. *Constr. Sci. Mater.* (2023) 18, 607–68. doi: 10.1080/10426914.2023.201769
- Shen, Z.H., Li, W.G., and Zhang, Q. Tensile behavior of high-performance inorganic hybrid composite of polypropylene and glass fiber for civil engineering. *Constr. Build. Mater.* (2023) 403, 131617. doi: 10.1016/j.conbuildmat.2023.131617

24. Abujarir, R., and Awajan, A. Genetic algorithms: theory, genetic operators, solutions, and applications. *Eng. J. Sci.* (2024). 17(1245–36). doi: 10.1007/s12065-023-09822-z
25. D'Agostino, D., Moudri, F., and Minichadze, E. Deep genetic algorithm-based workflow for multi-objective optimization of net zero energy buildings integrating sustainable assessment. *Energy Buildings*. (2023). 294:112941. doi: 10.1016/j.enbuild.2023.112941
26. Sidani, A., Shihawi, Y., and Elah, E. Multi-objective genetic algorithm optimization model for energy efficiency of residential building envelope under different climate conditions in Egypt. *Int. J. Climate Change*. (2023). 23:1244–55. doi: 10.1080/10672569.2023.2266398
27. Wang, L., Li, G., and Zhao, D. Multi-objective optimization of ac anti-reflection AR/VG/2A2B hexamethylene window for building energy saving. *Energy*. (2024). 289:129799. doi: 10.1016/j.energy.2023.129799
28. Shakh, A., Fathy, A., Mahdy, M., Rahman, A., Alota, M., Khatib, K., et al. Glazing systems utilizing phase change materials: micro-optical characteristics, potential for energy conservation, role in reducing carbon emissions, and impact on thermal discomfort. *Energy Buildings*. (2024). 311:114711. doi: 10.1016/j.enbuild.2024.114711
29. Yoh, C., Friesen, P., Dapoch, A., Sauerwald, S., and Maruy, R. Daylight quality: high-transmittance glass versus low-transmittance glass-effects on daylight quality, health, cognition and energy consumption. *Arch. Med.* (2024). 94:2292271. doi: 10.1081/036039860.2023.2292271

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