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**New multidimensional approach to investigate exteroceptive
and interoceptive predictors of health and well-being**

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CHAPTER 1

1. Introduction

1.1 Theoretical background on Body Representation

The representation of the human body is a fundamental, complex and dynamic process that emerges from the continuous integration of sensory signals from multiple sources, including vision, touch, proprioception, and the vestibular system (Graziano & Botvinick, 2002; Medina & Coslett, 2016). These sensory modalities provide fundamental information for motor control, spatial orientation, and bodily self-awareness, allowing for a stable and coherent perception of one's own body (Blanke, 2012; De Klerk et al., 2021; Ehrsson, 2012). This integration is essential for distinguishing self from non-self, a crucial process underpinning body ownership and the sense of agency (Tsakiris, 2010).

Our senses act as the entry gates through which external and internal stimuli are perceived and processed. At any given moment, we receive numerous sensory inputs from our environment, and the brain must selectively integrate these signals to create a unified experience of the body. Sensory information about the body comes from both the external world (*exteroception*) and the internal states of the body (*interoception*). While exteroception includes sensory modalities such as sight, hearing, and touch, interoception encompasses the perception of internal bodily states, including temperature, pain, itch, muscular and visceral sensations, hunger, thirst, and other internal cues (A. D. Craig, 2002; Pollatos & Herbert, 2018). These complementary sensory modalities must be integrated to maintain a coherent sense of the body and its boundaries. In addition to exteroception and interoception, proprioception constitutes a third crucial modality contributing to bodily self-consciousness. Proprioceptive signals originate from muscles, joints, and tendons, and provide continuous feedback about limb position, movement, and force, allowing for real-time monitoring and control of bodily actions (Proske & Gandevia, 2012).

From a historical perspective, Sherrington (1906) introduced the tripartite distinction between exteroception, interoception, and proprioception, establishing a foundational classification of somatic senses still referenced in contemporary embodiment research.

The predictive coding model suggests that the brain continuously generates predictions about bodily states based on prior experience, updating these representations through sensory feedback (Apps & Tsakiris, 2014; Seth, 2013). Within this framework, exteroception provides flexible and adaptive representations of the body in response to environmental changes, whereas interoception ensures stability and coherence of bodily self-awareness (Seth, 2013; Seth et al., 2012; Tsakiris, 2017). The balance between these two systems is fundamental for bodily self-consciousness, as interoceptive and

exteroceptive signals continuously interact to maintain a stable sense of the bodily self. Disruptions in this balance have been experimentally linked to increased susceptibility to bodily illusions (Tsakiris, 2017; Tsakiris et al., 2011), and clinically associated with altered bodily awareness in schizotypy, schizophrenia, anxiety, and depression (Ferri & Gallese, 2018; Gallese & Ferri, 2014; Khalsa et al., 2018; Torregrossa et al., 2022; Torregrossa & Park, 2022). However, such alterations are not limited to clinical populations, for instance, normal aging is also characterized by progressive changes in body representation (Raimo et al., 2021), in interoceptive awareness (Khalsa et al., 2009) and multisensory integration (Mozolic et al., 2011). Aging is characterized by significant changes in all sensory systems and a variety of cognitive functions. Given the extent of age-related alterations in sensation, perception, and cognition, as well as in the anatomy and physiology of the brain, it is not surprising that multisensory integration also changes with age.

1.2 The Minimal Self and Bodily Self-Awareness

The concept of bodily self-awareness has been explored from both phenomenological and neuroscientific perspectives, with a key distinction between different levels of self-consciousness. The *minimal self* constitutes the most fundamental sense of selfhood and emerges from bodily experience. The minimal self describes the immediate, pre-reflective experience of selfhood derived from sensory information (Blanke & Metzinger, 2009; Gallagher, 2000). This pre-reflective self-awareness is supported by the continuous integration of sensory signals that differentiate the self from external objects and agents. Experimental paradigms, such as the rubber hand illusion (Botvinick & Cohen, 1998) and full-body illusions (Petkova & Ehrsson, 2008), demonstrate that body representation is malleable and influenced by external stimuli and multisensory integration highlighting the role of sensory congruence in the dynamic modulation of body perception. These illusions reveal that synchronous stimulation between visual, tactile, and proprioceptive cues can induce a temporary sense of ownership over external body parts or even whole-body representations (O’Kane et al., 2024). This phenomenon underscores the crucial role of sensory congruence in dynamically modulating body perception. Previous studies suggest that discrepancies between expected and actual sensory feedback can result in distortions in body awareness, reinforcing the idea that body representation is continuously updated through multisensory, exteroceptive and interoceptive feedback (Kilteni et al., 2015; Seth, 2013).

1.3 The Role of Interoception in Body Representation

Interoception refers essentially to sensations stemming from inside the body such as heartbeats, breaths, temperature, hunger, and thirst (A. D. Craig, 2009; Critchley et al., 2004; Mayer et al., 2006). According to Garfinkel et al. (2015) interoception can be divided into three distinct components: interoceptive accuracy, interoceptive sensibility and interoceptive awareness. Interoceptive accuracy refers to the objective ability to detect internal bodily sensations. The most common approach for the assessment is the tracking method, originally proposed by Schandry (R. Schandry, 1981), which assesses the accuracy to feel one's own heartbeat by counting them in a given time interval via behavioural tasks (R. Schandry, 1981). Interoceptive Sensibility refers to a dispositional tendency to be internally focused and reflects the subjective evaluation or confidence in recognizing these internal bodily sensations. Usually, interoceptive sensibility is measured via self-reported questionnaires such as questionnaire (Mehling et al., 2012; Poli, Giovanni, et al., 2021). Another indicator of interoceptive sensibility is the mean of individual confidence ratings in interoceptive accuracy tasks (Garfinkel et al., 2015). Interoceptive awareness, represent the metacognitive awareness of one's interoceptive abilities and is commonly assessed by comparing interoceptive accuracy and sensibility (Forkmann et al., 2016; S. Garfinkel et al., 2013.). Functionally, interoceptive awareness points out bodily needs, such as the need to drink or to eat, and provides information on emotional state (Calì et al., 2015). Interoception also plays a crucial role in shaping body representation (A. D. Craig, 2002). The malleability of body representation is influenced not only by multisensory integration (Tsakiris et al., 2011), but also by interoceptive processing (Suzuki et al., 2013).

Disruptions in interoception have been increasingly recognized as a factor implicated in psychiatric conditions including schizotypy, schizophrenia, anxiety and depression, where alterations in bodily self-awareness are central aspects (Ardizzi et al., 2016; Khalsa et al., 2018; Torregrossa et al., 2022).

1.4 Exteroception and Multisensory Integration in Body Representation

In recent years, various researchers have demonstrated that body representation has a multisensory nature as it is based on the integration of information from different sensory modalities (touch, proprioception, vision, vestibular signals) (Parma et al., 2024). Exteroception refers to the perception of external stimuli that comes from the environment and interacting with the body's surface. This sensory domain includes vision, touch, and audition, which provide continuous feedback about the body's position, spatial orientation, body boundaries, and interactions with external objects.

Exteroception is fundamental for constructing an accurate and adaptable representation of the body in space, allowing individuals to navigate and interact efficiently with their surroundings.

In the context of body representations, it is important distinguishing between two key aspects of exteroception, the body schema, and body image. The body schema consists of sensorimotor representations of the body that guide action, operating implicitly and automatically to coordinate movement (de Vignemont, 2010; Longo, 2016). On the other hand, body image refers to our subjective experience of the physical structure of our body and encompasses all explicit and cognitive-affective representations of the body, including its shape, size, and aesthetic perception (Longo, 2016). While body schema supports motor functions and postural control, body image integrates perceptual, conceptual, and emotional aspects of bodily awareness (de Vignemont, 2010; Pitron et al., 2018; Sattin et al., 2023).

Multisensory Integration refers to the process by which inputs from two or more sensory modalities are combined by the nervous system to form a stable and coherent percept of the world (Stein et al., 2014). It is crucial in aligning bodily signals and maintaining a coherent sense of self, particularly when there is sensory conflict or ambiguity.

From a theoretical perspective, *the embodied cognition* (Varela et al., 1993) proposes that bodily experience shape cognitive and perceptual processes, emphasizing that cognition is grounded in bodily experience. This integrated perspective highlights that body representation is not only a passive reflection of sensory inputs but is dynamically shaped by interactions between sensorimotor, interoceptive, and cognitive processes. The theory agrees on the idea that exteroception, interoception, and multisensory integration work together to create a unified experience of "being in the body." Accordingly, bodily experience is inherently multifaceted, involving the coordination of sensory, motor, and cognitive systems. This integrated experience enables efficient interaction with the environment, shaping perception, cognition, and behaviour. Different body representations interact with one another and often engage multisensory processes. For instance, spatial tactile acuity and body structural representation provide detailed sensory feedback that refines our understanding of body boundaries and shape, influencing both body image and sensorimotor functions (Teufel et al., 2010). At the same time, multisensory integration synthesizes information across modalities (e.g., vision, touch, proprioception), facilitating motor actions, particularly within peripersonal space that refers to the immediate area surrounding the body. Temporal tactile acuity and multisensory temporal resolution are crucial for coordinating actions that require rapid, precise sensory-motor interactions. Finally, interoception enriches bodily experience by linking external sensory perceptions to internal sensations, influencing both body image and sensorimotor functions.

1.5 Psychiatric Disorders and altered Body Representation

Alterations in body representation and multisensory integration have been extensively documented in psychiatric conditions such as schizotypy, schizophrenia, anxiety, and depression. These conditions are often characterized by disruptions in interoceptive, exteroceptive, and multisensory processing, leading to distortions in body awareness.

In recent years, the phenomenological concept of embodiment has become central in interdisciplinary fields, including psychiatry (Fuchs & Schlimme, 2009). Within schizophrenia research, the cognitive approach has traditionally focused on analysing mental processes and cognitive distortions considered central to the disorder, such as deficits in attention, memory, and executive functions (Bowie & Harvey, 2006). In contrast, the phenomenological approach emphasizes the role of bodily experience and the mind-body relationship in the onset and manifestation of psychotic symptoms. This approach posits that abnormal bodily experiences and distorted body representations play a crucial role in shaping cognitive processes and sense of self in individuals with schizophrenia (Fuchs & Schlimme, 2009, Sass & Parnas, 2003). Accordingly, it has been proposed that the core aspect of selfhood (“minimal self”) impacted in early schizophrenia and in schizotypal conditions involves automatic, pre-reflective and implicit bodily functioning, as well as attuning to others at an intracorporeal level (Ferri, Frassinetti, Ardizzi, et al., 2012; Parnas, 2003; Sass, 2003), and blurred self-other boundaries (B. Nelson et al., 2012). According to the dimensional approach to psychosis, there exists a continuum ranging from individuals with low levels of schizotypy to diagnosed schizophrenia patients. Schizotypy is considered a subclinical expression of schizophrenia symptoms within the general population. Schizotypal traits typically encompass three dimensions (Davidson et al., 2016; Raine & Raine, 1991): cognitive-perceptual traits (positive symptom-like experiences), such as unusual perceptual experiences and odd beliefs, which are analogous to the positive symptoms of schizophrenia (e.g., hallucinations and delusions); interpersonal traits (negative symptom-like experiences), such as social withdrawal and emotional flatness, which correspond to the negative symptoms of schizophrenia (e.g., social dysfunction, diminished motivation, and emotional expression); and disorganized traits (cognitive disorganization-like experiences), such as odd speech and behaviour, which align with the disorganized symptoms of schizophrenia (e.g., disruptions in thought processes and basic cognitive impairments) (Keefe & Harvey, 2012; Raine et al., 1994). This spectrum reflects the manifestation of symptoms with varying degrees of severity and functional impairment (Kwapil & Barrantes-Vidal, 2015; M. T. Nelson et al., 2013).

Several studies investigating different dimensions of body representations have empirically supported this proposal (Debbané & Mohr, 2015; Di Cosmo, Costantini, Ambrosini, et al., 2021; Lenzenweger,

2006; Raine, 2006). For instance, disruptions in the multisensory representation of the *peripersonal space* (PPS), which refers to the space immediately surrounding the body, have been observed in individuals with schizophrenia and high levels of schizotypy (Di Cosmo et al., 2018). Similarly, both patients with schizophrenia (Costantini et al., 2020) and individuals with high levels of schizotypy (Fotia et al., 2022) exhibit impairments in the *body structural representation*. These impairments can manifest, for example, as reduced accuracy in a finger localization task where participants are asked to identify pairs of fingers touched by the examiner while integrating tactile and proprioceptive information, with their hands hidden from view. Interestingly, the patients' performance in this task correlates with their scores on the Scale for the Assessment of Basic Symptoms (SPI-A), indicating a relationship between body representation deficits and symptom severity (Costantini et al., 2020).

Moreover, other bodily-self abnormalities have been identified, including *body image* alterations evaluated as experiences of body distortion worsened in passive symptoms (Graham-Schmidt et al., 2016), *spatial tactile acuity* showing a reduced tactile discriminability observed via the two-point discrimination task (Michael & Park, 2016), and *sensorimotor functions* with a diminished motor representations of one's body parts assessed through the hand laterality judgment task (Ardizzi et al., 2020). Also, the capacity to remap environmental stimuli within the body space, an essential function for delineating the boundaries between self and the external world, seems to be already compromised in individuals with high schizotypy, as evidenced by their performance on tasks requiring the integration of tactile and proprioceptive cues regarding current body posture with other external spatial information (Ferri et al., 2016).

Body representations are predominantly multisensory, and recent research underscores a crucial connection between deficits in multisensory integration and self-disorders in schizophrenia (Postmes et al., 2013). For example, De Gelder et al. (2002) identified impaired audiovisual integration in schizophrenia patients, while Williams et al. (Williams et al., 2010) found altered integration of tactile and proprioceptive signals in those with schizotypy. Further investigations have delved into the temporal aspects of multisensory processing, which is thought to be the scaffolding for perception and cognition (Wallace & Stevenson, 2014). These studies have revealed altered temporal sensitivity in schizophrenia patients and those with high scores on the *Schizotypal Personality Questionnaire* (SPQ) (Di Cosmo, Costantini, Ambrosini, et al., 2021; Ferri et al., 2017, 2018; Fotia et al., 2022). In tasks like simultaneity judgment, where individuals assess if stimuli from different senses occurred simultaneously, schizophrenia patients and those with high scores on the Schizotypal Personality Questionnaire (SPQ) exhibit a broader threshold for perceiving simultaneity compared to healthy

individuals or those with lower SPQ scores. These findings suggest that individuals with high schizotypy, akin to schizophrenia patients, display abnormalities in multisensory processing.

Recently, it has been proposed that a crucial aspect of the human minimal self is interoception and that the developmental trajectory of interoception interacts with exteroceptive minimal-self components. The role of interoception in schizophrenia has received relatively less attention until recent years (Ardizzi et al., 2016; Rabellino et al., 2023; Torregrossa et al., 2022). However, emerging evidence suggests that interoceptive processes may also be relevant in schizophrenia, shedding new light on the complex interplay between bodily awareness and psychotic symptoms. For example, changes in the ability to perceive and identify interoceptive signals coincide with improvements in sensorimotor and multisensory body representations (Musculus et al., 2021; Tsakiris et al., 2011). Interoception plays a crucial role in the experience of a unified bodily self (Serino et al., 2013; Tsakiris, 2017). Notably, impaired interoceptive representations have been found to contribute to the disrupted sense of bodily self often observed in individuals along the schizophrenia spectrum (Ardizzi et al., 2016; Rabellino et al., 2023; Torregrossa et al., 2022). Garfinkel et al. (2015) identified three distinct aspects of interoception: interoceptive accuracy referring to the accuracy in detecting internal bodily sensations, interoceptive sensibility referring to the subjective evaluation of experiencing internal bodily sensations (Critchley & Garfinkel, 2017), and interoceptive awareness referring to the metacognitive awareness of one's interoceptive ability. The first two aspects have been shown to be reduced in chronic schizophrenia patients (Ardizzi et al., 2016; Koreki et al., 2021; Torregrossa et al., 2022); as well as in youth with psychotic-like experiences (Barbato et al., 2021).

Anxiety and depression are increasingly viewed not only as disorders of cognition and emotion but also as conditions rooted in disrupted bodily processing (Quadt et al., 2018). Recent approaches indicate that particularly interoceptive aspects might represent *transdiagnostic mechanisms* that confer common vulnerability traits across multiple disorders including anxiety and depression (Jenkinson et al., 2024; Khalsa et al., 2018; Nord & Garfinkel, 2022; Paulus & Stein, 2010; Saltafossi et al., 2025).

Anxiety disorder is characterized by an exaggerated expression of normative defensive responses, manifesting as heightened vigilance, persistent worry, and an amplified perception of threat (American Psychiatric Association, 2013; Kenwood et al., 2021). On a physiological level, this heightened state of reactivity manifests as increased heart rate, muscle tension, and other somatic symptoms (Oexle & Reuster, 2023), which in turn amplify the experience of anxiety (Paulus & Stein, 2006). An emerging area of interest is the role of bodily awareness in this disorder (Orphanidou et al., 2023) particularly through the dimensions of interoception and the processing of external sensory

stimuli. The misalignment of interoceptive processing may play a significant role in the development of anxiety disorders, as the misattribution of bodily sensations has been identified as a key factor in the onset of panic and related anxiety symptoms (Clark et al., 1997). Individuals with heightened tendency to focus the attention on internal body signals tend to detect internal physiological changes more readily, which may contribute to excessive bodily vigilance and symptom exacerbation. Hence, several studies show that higher interoceptive accuracy is related to higher anxiety traits (Saltafossi et al., 2025; Tsakiris & De Preester, 2018).

Conversely, depression is a mood disorder characterized by pervasive feelings of sadness, anhedonia, and a diminished capacity to experience pleasure (Chand & Arif, 2023; ICD-10: International Statistical Classification of Diseases and Related Health Problems: Tenth Revision, 2003) alongside neurovegetative symptoms, such as changes in sleep patterns, appetite, and energy levels that further contribute to its debilitating impact (Depression. Clinical, Experimental and Theoretical Aspects, 1969). Depression is also associated with autonomic dysfunction, manifesting as reduced heart rate variability (Dawson et al., 1977; Quadt et al., 2018). The role of interoception in low mood and clinical depression has been also investigated in several studies. Research suggests that interoceptive accuracy is reduced in low to moderate, but not severe depression (Dunn et al., 2007). Furthermore, a negative correlation between heartbeat perception and depressive symptoms has been reported (Pollatos et al., 2009), indicating that individuals with lower interoceptive accuracy may experience emotions with diminished intensity.

Increasing evidence suggests that alterations in exteroceptive processing also contribute to anxiety and depression. For instance, anxiety and fear can result in changes in the perception of the external environment (Lee et al., 2024). This is particularly relevant for the peripersonal space (PPS) dimension, the immediate area surrounding the body where interactions with objects and others occur (Serino, 2019). PPS is dynamically shaped by multisensory integration and serves both defensive and social functions. Research indicates that trait anxiety is associated with an expanded PPS, meaning that anxious individuals perceive threats as closer than they are, reinforcing hypervigilance and avoidance behaviours (Iachini et al., 2015; Sambo & Iannetti, 2013). This suggests that anxiety alters spatial perception in a way that prioritizes self-protection by extending the body's safety margin (Iachini et al., 2015). Furthermore, threatening stimuli appear to distort perceptual space and time, leading to an overestimation of the proximity of danger and a misinterpretation of environmental cues (Lee et al., 2024; McNaughton & Corr, 2004). These findings suggest that anxiety can lead to perceptual aberrations, including mis-estimation of space and time (Vagnoni et al., 2012, 2015). No study has investigated PPS in depression. Disruptions in space and time perception observed in anxiety may reflect broader alterations in multisensory integration (Lee et al., 2024; Vagnoni et al.,

2012, 2015). Although direct evidence remains limited, it is well-documented that multisensory processes are fundamentally involved in bodily self-consciousness (Aspell et al., 2012) and emotion regulation, that are often altered in both anxiety and depression (Quadt et al., 2018).

Body image refers to our subjective experience of the physical structure of our body and encompasses all explicit and cognitive-affective representations of the body, including its shape, size, and aesthetic perception (Longo, 2016). Body image integrates perceptual, conceptual, and emotional aspects of bodily awareness (de Vignemont, 2010; Pitron et al., 2018; Sattin et al., 2023). Body image is defined as a person's body-related self-perceptions and self-attitudes, including body-related thoughts, feelings, and behaviours (Cash, 2004). The concept of body image includes at least two components: perceptual body size (i.e., estimation of one's body size, which can be distorted when different from actual body size) and attitudinal body image (i.e., affective, cognitive, and behavioural concerns with one's body size) (Paans et al., 2018). Growing evidence suggests that body image disturbances may also play a role in affective disorders. In individuals with depression, the body image has characteristics typical to the disorder, influencing how they relate to themselves and their environment. Typical to the body image of depression sufferers experience low energy, discomfort in the body during social interaction, and a tendency to distance oneself from sensing the body (Pylvänäinen et al., 2021). Major depressive disorder and high depressive symptoms are associated to higher body image dissatisfaction and to a larger perceptual body size (Paans et al., 2018).

In relation to anxiety, body image has been primarily investigated in adolescent populations (e.g. Dou et al., 2023; Vannucci & Ohannessian, 2017), it is considered as a central aspect in the development of emotional and social difficulties. Anxiety, particularly social anxiety, has been consistently linked to increased body-related dissatisfaction, which may contribute to distortions in body image perception (Dou et al., 2023). While anxiety has often been viewed as a contributing factor to body image disturbances, the reverse causal direction is also plausible. Distorted body image may precede and contribute to the onset of anxiety, particularly in contexts involving social evaluation. Individuals who experience heightened dissatisfaction with their physical appearance may become hypervigilant to how they are perceived by others, leading to increased social avoidance and anxious anticipation of body-related scrutiny. This bidirectional relationship suggests that negative body image may not only be a correlate or consequence of anxiety, but also a contributing factor to its development and maintenance. Findings suggest that body image dissatisfaction is associated with concurrent symptoms of multiple anxiety disorders (Vannucci & Ohannessian, 2017).

1.6 Aging and altered Body Representation

Aging is characterized by progressive changes in body representation, primarily affecting in the integration of interoceptive and multisensory information (Freiherr et al., 2013; Kuehn et al., 2018; MacCormack et al., 2021) that are crucial for maintaining bodily self-awareness and adaptive interaction with the environment. As individuals age, the progressive change in bodily functions contributes to declines in cognitive (Murman, 2015) and daily life functioning (Kuehn et al., 2018). These changes are closely linked to the progressive decline in interoceptive abilities. Research shows that older adults experience significant declines in interoceptive accuracy and awareness (Khalsa et al., 2009), which are linked to reductions in physical functioning and increased dependence in daily activities. As a result, older adults may experience difficulties in tasks requiring bodily awareness, emotional regulation, and interaction with their environment (Charles & Carstensen, 2010; Sardella et al., 2023). For older adults, these difficulties often manifest in reduced functional body capacity, an important indicator of health that significantly compromises the quality of life and causes a heavy social impact with increased use of medical care (Guralnik et al., 1996). The decline in interoceptive abilities with age has also been associated with reduced capacity for emotional self-regulation, as aging-related disruptions in bodily awareness may contribute to increased anxiety and depressive symptoms in older populations (Murphy et al., 2018). Hence, interoception represents a central aspect for better understanding the mechanisms underlying active aging, particularly in relation to physical functioning, well-being and daily functioning. Functionally, interoceptive awareness points out bodily needs, such as the need to drink or to eat, and provides information on emotional state (Calì et al., 2015). Individual interoceptive accuracy is commonly assessed as the ability to feel one's own heartbeat via behavioural tasks (R. Schandry, 1981) while, interoceptive sensibility, that is the subjective beliefs about interoceptive signals, is measured via self-reported questionnaires (Garfinkel et al., 2015). Finally, interoceptive awareness is commonly assessed by comparing interoceptive accuracy and sensibility. Importantly, research shows significant declines in both interoceptive accuracy (Khalsa et al., 2009) and interoceptive sensibility (Khalsa et al., 2009; Murphy et al., 2018) declines with age.

As individuals age, there is an unnoticed but significant increase in sensory thresholds across various modalities, including vision, hearing, smell, touch, temperature sensation, and pain perception. Age-related sensory decline is the result of both peripheral degeneration and central processing deficits, and their relative contributions vary across sensory modalities. In the auditory and visual systems, much of the initial sensory loss is attributable to peripheral damage, such as loss of hair cells in the cochlea or photoreceptor degeneration in the retina (Pelle & Wingfield, 2016; Owsley, 2011). However, age-related changes in central neural processing, including reduced signal-to-noise ratio,

impaired cortical inhibition, and decreased efficiency of multisensory integration—also play a significant role, particularly in higher-order perceptual and sensorimotor functions (Li & Lindenberger, 2002). These central mechanisms become especially relevant when individuals must integrate multiple sensory cues for complex tasks, such as balance control or dual-task walking. Therefore, sensory decline in aging cannot be attributed solely to peripheral deficits, but should be understood as a multilevel deterioration that compromises both input quality and central integration. This means that stronger and more pronounced stimuli are required for sensory information to be consciously perceived. Such sensory changes impair the brain's ability to acquire, process, and integrate information from the body and the environment, creating significant challenges for movement autonomy and the performance of daily activities (Gescheider et al., 1994; Gibson & Farrell, 2004). For instance, difficulties in detecting and interpreting sensory cues can reduce an individual's ability to navigate their surroundings safely and effectively. The reliability of sensory signals plays a crucial role in multisensory integration, particularly in defining the time interval within which stimuli from different sensory modalities are perceived as simultaneous or causally connected, also known as the *temporal binding window* (McGovern et al., 2022). In older adults, the ability to select and integrate sensory signals diminishes, leading to less precise and more variable sensory processing. This reduced sensory reliability results in a broader temporal binding window, which can negatively impact coordination and perception (Basharat et al., 2019; Brooks et al., 2018; Cao et al., 2019). Research shows that older adults with a wider temporal binding window are more likely to experience falls, suggesting a direct link between multisensory integration and physical stability (Mahoney, et al., 2019; McGovern et al., 2022; Setti et al., 2011).

Research on young individuals suggests that interoception modulates the online multisensory integration processes (Tsakiris et al., 2011) underlying several types of body representations, such as the representation of the peripersonal space (Ardizzi & Ferri, 2018) that refers to the area immediately surrounding the body, where interactions with objects and other individuals occur. It is dynamically shaped by multisensory integration (Serino, 2019), combining visual, tactile, and proprioceptive inputs to create a safety margin for action and interaction. Multisensory integration refers to the brain's ability to combine information from different sensory modalities (e.g., visual, auditory, tactile) to form a coherent representation of the body and the surrounding environment (Ernst & Bühlhoff, 2004). In aging, disruptions in this process can lead to difficulties in spatial orientation and motor coordination (Chepishева, 2023). In older adults, altered multisensory processes are associated with an increased risk of falls (Chepishева, 2023; Mahoney, et al., 2019) and diminished multitasking abilities (Kuehn et al., 2018). Moreover, interoception seems to be relevant also for tactile perception (Al et al., 2020) and sensorimotor abilities, such as mental rotation of body parts (Raimo et al., 2021).

Mental rotation of body parts involves the ability to mentally visualize and manipulate the position of one's own limbs or other body segments and is essential for planning movements and interacting with the environment. These processes are closely linked to body image, which refers to the perception, thoughts, and feelings about one's own body. Body image is not only shaped by external sensory inputs (e.g., visual and tactile feedback) and motor experiences but also by interoceptive signals, which provide crucial information about the internal state of the body (Ainley et al., 2012). This interplay between interoception and body image (Badoud & Tsakiris, 2017) highlights the importance of internal bodily signals in constructing a coherent and adaptive sense of self. Previous literature suggests that interoceptive deficits in aging not only affect internal bodily awareness but also disrupt the integration of multisensory signals necessary for effective interaction with the environment. This underscores the importance of interoception as a central mechanism underlying age-related declines in daily function activity.

1.7 Overview of the thesis

In the present thesis, we aimed to develop and validate a comprehensive behavioural battery designed to assess a wide range of bodily processes involved in body representation. This battery was designed to evaluate both exteroceptive and interoceptive bodily dimensions and includes objective tasks and self-report questionnaires. Specifically, the battery evaluates body image, spatial tactile acuity, body structural representation, multisensory integration, multisensory temporal resolution, peripersonal space, temporal tactile acuity, sensorimotor functions, and the three dimensions of interoception: accuracy, sensibility, and awareness. The dimensions and the respective assessment are summarized in table 1.

Table 1 Exteroceptive and interoceptive dimensions included in the battery

Exteroceptive	
Dimensions	Assessment
Body Image	PFRS - Photographic Figure Rating Scale Task BUT A B Body Uneasiness test (A & B)
Spatial tactile acuity	TPD - Two-Point Discrimination Task
Body structural representation	FL - Finger Localization Task
Multisensory Integration (MI)	MSI - Multisensory Integration Task
Multisensory Temporal Resolution	SJ - Simultaneity judgments Task
Peripersonal space	PPS - PeriPersonal Space Task
Temporal tactile acuity	TOJ-u - Temporal-order judgment Task (Uncrossed)
Sensorimotor functions	TOJ-c - Temporal-order judgment Task (Crossed) LJ - Laterality judgement task

Interoceptive	
Dimensions	Assessment
Interoceptive Accuracy	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task
Interoceptive Sensibility	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task BPQ - Body Perception Questionnaire MAIA - Multidimensional Assessment of Interoceptive Awareness
Interoceptive Awareness	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task

The rationale behind this battery is grounded in embodied cognition and predictive coding theories, which propose that bodily perception emerges from the continuous integration of external and internal sensory signals. Through the integrated assessment of bodily dimensions, this battery provides a novel multidimensional approach to understanding the role of the body in mental and physical well-being. We also implemented Partial Least Squares Regression (PLSR) as a machine learning approach for exploring complex, collinear, and high-dimensional data. This approach allowed us to model the relationship between multiple bodily dimensions and psychological or physical outcomes, providing interpretable and generalizable results across different populations and clinical domains.

To validate and apply this methodological approach, we tested the battery across four different studies, each focusing on a different target, schizotypy, anxiety, depression and aging, addressing different research questions related to the domain of bodily self and different physical and mental condition. In Study 1, we investigated the predictive role of interoceptive and exteroceptive bodily dimensions to schizotypal traits. In more details, we tested the hypothesis that different schizotypal personality traits (cognitive-perceptual, interpersonal, disorganized) are influenced by different exteroceptive and interoceptive bodily dimensions. In Study 2, we examined how the same interoceptive and exteroceptive bodily processes contribute to anxiety and depression, exploring shared and specific predictors across these affective disorders. In Study 3, we applied the battery to a sample of older adults to investigate whether early changes in interoception, which influence bodily processes, can reliably predict declines in daily life functioning. Then, we explore whether and how the inclusion of exteroceptive bodily dimensions interact with interoceptive bodily dimensions to predict daily functioning. Finally, in Study 4, we focused on a subset of bodily dimensions (interoceptive accuracy, sensibility, awareness, multisensory temporal resolution, and sensorimotor function), to investigate whether interoceptive processing and multisensory integration could predict physical functioning in older adults. The aim was to explore whether age-related declines in these processes could explain individual differences in physical health and functioning, as measured by the SF-36 questionnaire.

Together, these studies demonstrate the flexibility and utility of the battery, providing a novel framework for integrating bodily dimensions into the study of psychological and physical well-being in different conditions and across the lifespan.

CHAPTER 2.

Predictive role of exteroceptive and interoceptive bodily dimensions to schizotypal personality traits

1 Introduction

Schizophrenia research has been conducted using two main approaches: cognitive and phenomenological. The former has traditionally focused on analysing mental processes and cognitive distortions central to the disorder, such as deficits in attention, memory, and executive functions. The latter emphasizes the role of bodily experience and the mind-body relationship in the onset and manifestation of psychotic symptoms. Following the phenomenological approach, it has been proposed that the core aspect of selfhood, referred to as the "minimal self," involves automatic, pre-reflective, and implicit bodily functioning. This concept also includes connecting with others at an intracorporeal level (Ferri, Frassinetti, Mastrangelo, et al., 2012; Parnas, 2003; Sass, 2003) and experiencing blurred self-other boundaries (B. Nelson et al., 2012). According to the continuum hypothesis of schizophrenia, these aspects of the "minimal self" are altered in early schizophrenia and schizotypal conditions (Debbané & Mohr, 2015; Di Cosmo, Costantini, Ambrosini, et al., 2021; Lenzenweger, 2006; Raine, 2006). Several studies investigating different dimensions of body representations have empirically supported this proposal (Debbané & Mohr, 2015; Di Cosmo, Costantini, Ambrosini, et al., 2021; Lenzenweger, 2006; Raine, 2006).

For instance, disruptions in the representation of the *peripersonal space* have been observed in individuals with schizophrenia and high levels of schizotypy (Di Cosmo et al., 2018). Similarly, both patients with schizophrenia (Costantini et al., 2020) and individuals with high levels of schizotypy (Fotia et al., 2022) exhibit impairments in the *body structural representation* (Fotia et al., 2022), *body image* (Graham-Schmidt et al., 2016; Lenzenweger, 1994), *spatial tactile acuity* (Lenzenweger, 2000; Michael & Park, 2016), and *sensorimotor functions* (Ardizzi et al., 2020; Ferri et al., 2016). Body representations are predominantly multisensory, and recent research underscores a crucial connection between deficits in multisensory integration and self-disorders in schizophrenia (Postmes et al., 2013). For example, De Gelder et al. (De Gelder et al., n.d.) identified impaired audiovisual integration in schizophrenia patients, while Williams et al. (Williams et al., 2010) found altered integration of tactile and proprioceptive signals in those with schizotypy. Further investigations have delved into the temporal aspects of multisensory processing, which is thought to be the scaffolding for perception and cognition (Wallace & Stevenson, 2014). These studies have revealed altered temporal sensitivity in schizophrenia patients and those with high scores on the Schizotypal

Personality Questionnaire (SPQ)(Di Cosmo, Costantini, Ambrosini, et al., 2021; Ferri et al., 2017, 2018; Fotia et al., 2022).

Recently, it has been proposed that a crucial aspect of the human minimal self is interoception and that the developmental trajectory of interoception interacts with exteroceptive minimal-self components. For example, changes in the ability to perceive and identify interoceptive signals coincide with improvements in sensorimotor and multisensory body representations (Musculus et al., 2021; Tsakiris et al., 2011). Interoception plays a crucial role in the experience of a unified bodily self (Serino et al., 2013; Tsakiris, 2017). Notably, impaired interoceptive representations have been found to contribute to the disrupted sense of bodily self often observed in individuals along the schizophrenia spectrum (Ardizzi et al., 2016; Rabellino et al., 2023; Torregrossa et al., 2022). Garfinkel et al. (2015) identified three distinct aspects of interoception: interoceptive accuracy referring to the accuracy in detecting internal bodily sensations, interoceptive sensibility referring to the subjective evaluation of experiencing internal bodily sensations (Critchley & Garfinkel, 2017), and interoceptive awareness referring to the metacognitive awareness of one's interoceptive ability. The first two aspects have been shown to be reduced in chronic schizophrenia patients (Ardizzi et al., 2016; Koreki et al., 2021; Torregrossa et al., 2022); as well as in youth with psychotic-like experiences (Barbato et al., 2021).

Therefore, abnormalities in both exteroceptive and interoceptive body representations play a crucial role in shaping bodily phenomenological experiences across the schizophrenia-schizotypy continuum. Building on this reasoning, we hypothesize that these abnormalities may differentially predict the symptom-like traits observed in schizotypy. In support of the continuum hypothesis of schizophrenia, schizotypy is considered a subclinical expression of schizophrenia symptoms within the general population. Schizotypal traits typically encompass three dimensions (Davidson et al., 2016; Raine & Raine, 1991): cognitive-perceptual traits (positive symptom-like experiences), such as unusual perceptual experiences and odd beliefs, which are analogous to the positive symptoms of schizophrenia (e.g., hallucinations and delusions); interpersonal traits (negative symptom-like experiences), such as social withdrawal and emotional flatness, which correspond to the negative symptoms of schizophrenia (e.g., social dysfunction, diminished motivation, and emotional expression); and disorganized traits (cognitive disorganization-like experiences), such as odd speech and behaviour, which align with the disorganized symptoms of schizophrenia (e.g., disruptions in thought processes and basic cognitive impairments)(Keefe & Harvey, 2012).

The present study tested the hypothesis that different schizotypal personality traits are influenced by different exteroceptive and interoceptive bodily dimensions. To this aim, we administered a

behavioral battery designed to assess both exteroceptive and interoceptive body representations, as well as multisensory integration. The specific dimensions and tasks in this battery were selected based on literature concerning body representations and multisensory integration in schizotypy and schizophrenia (Fuchs & Schlimme, 2009). Rather than covering every aspect of body awareness, the battery emphasizes those most relevant to the schizophrenia spectrum. The exteroceptive measures focused on body image, body schema (defined as the unconscious mental representation of the body's position, movement, and spatial relations), and abilities related to multisensory integration. The battery's design aligns with the idea that bodily experience arises from continuous interaction between internal and external sensory inputs (Teufel et al., 2010), as supported by theoretical frameworks such as embodied cognition (Varela et al., 1993) and the body schema model (Gallagher, 2000).

These theories agree on the idea that exteroception, interoception, and multisensory integration work together to create a unified experience of "being in the body." Accordingly, bodily experience is inherently multifaceted, involving the coordination of sensory, motor, and cognitive systems. This integrated experience enables efficient interaction with the environment, shaping perception, cognition, and behaviour. Additionally, different body representations interact with one another and often engage multisensory processes. For instance, spatial tactile acuity and body structural representation provide detailed sensory feedback that refines our understanding of body boundaries and shape, influencing both body image and sensorimotor functions (Teufel et al., 2010). At the same time, multisensory integration synthesizes information across modalities (e.g., vision, touch, proprioception), facilitating motor actions, particularly within peripersonal space—the immediate area surrounding the body. Temporal tactile acuity and multisensory temporal resolution are crucial for coordinating actions that require rapid, precise sensory-motor interactions. Finally, interoception—the perception of internal bodily states such as heartbeat, hunger, or pain—enriches bodily experience by linking external sensory perceptions to internal sensations, influencing both body image and sensorimotor functions. To understand this complex interplay, we used Partial Least Squares Regression (PLSR), a supervised learning methodology. PLSR provides a robust approach for examining relationships between multiple predictors and outcomes, making it particularly well-suited for our multidimensional analysis. With this novel approach, we aim to identify both interoceptive and exteroceptive body dimensions that are associated with and differentially predict schizotypal traits, while accounting for interactions between these dimensions. By doing so, this study provides new insights into their specific contributions to schizotypy, advancing our understanding of their role in the risk of psychosis along the schizophrenia continuum.

2. Methods and materials

2.1. Participants

Sixty right-handed, healthy volunteers (36 females, mean age $\pm$ SD: 25.71 ± 5.47 years) participated in the study after providing written informed consent. Participants were recruited through an online questionnaire. No participant had a history of neurological, general medical or psychiatric conditions. No participants reported a family history of psychosis. The experimental protocol was approved by the Institutional Ethics Committee at the University G. d'Annunzio, Chieti-Pescara. All participants were assessed for their schizotypal personality traits using the Schizotypal Personality Questionnaire (Raine & Raine, 1991).

2.1.2 Schizotypal Personality Questionnaire (SPQ)

The Schizotypal Personality Questionnaire (Raine & Raine, 1991) is a validated questionnaire based on the diagnostic criteria of the DSM-III-R for schizotypal personality disorder. It consists of 74 items that measure the three-factor construct of schizotypy: cognitive-perceptual deficit, interpersonal deficit, and disorganization (Raine, 2006; Raine & Raine, 1991). Responses are dichotomous (yes/no), with one point assigned for each agreement with an item. The total SPQ scores ranged from 0 to 53 (mean $\pm$ SD: 22.58 ± 13.37); the cognitive-perceptual scores ranged from 0 to 26 (mean $\pm$ SD: 9.56 ± 7.46); the interpersonal scores ranged from 0 to 29 (mean $\pm$ SD: 11.3 ± 6.82); the disorganization scores ranged from 0 to 16 (mean $\pm$ SD: 4.83 ± 4.08).

2.2. Procedure

Each participant completed the entire battery, which comprised tasks and questionnaires evaluating either exteroceptive or interoceptive bodily dimensions (Table 1).

Table 1: Tasks and questionnaires evaluating either exteroceptive or interoceptive bodily dimensions.

Exteroceptive		
Dimensions	Assessment	Variables
Body Image	PFRS - Photographic Figure Rating Scale Task BUT A B Body Uneasiness test (A & B)	BMI (R), A(ctual), I(deal), O(ther), Δ AR, Δ IR, Δ OR. Pt. tot. A, Pt. tot. B.
Spatial tactile acuity	TPD - Two-Point Discrimination Task	C-che, O-che, U-che, U-thi, O-thi, C-thi.
Body structural representation	FL - Finger Localization Task	HIT
Multisensory Integration (MI)	MSI - Multisensory Integration Task	AUC-av, AUC-at, AUC-vt.
Multisensory Temporal Resolution	SJ - Simultaneity judgments Task	PSE-sj, JND-sj
Peripersonal space	PPS - PeriPersonal Space Task	PSE-pps
Temporal tactile acuity	TOJ-u - Temporal-order judgment Task (Uncrossed)	JND-toju, .
Sensorimotor functions	TOJ-c - Temporal-order judgment Task (Crossed) LJ - Laterality judgement task	JND-tojc, SC-toj. MRE-lh, MRE-rh.

Interoceptive		
Dimensions	Assessment	Variables
Interoceptive Accuracy	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task	Acc(uracy)-d Acc-c
Interoceptive Sensibility	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task BPQ - Body Perception Questionnaire MAIA - Multidimensional Assessment of Interoceptive Awareness	Con(fidence)-d Con-c Subscales: BOA- SUP-BOA/SUB Subscales: 1M-8M
Interoceptive Awareness	HBDT - Heart Beat Detection Task HBCT - Heart Beat Counting Task	Aw(areness)-d Aw-c

2.2.1 Exteroceptive Bodily Dimensions

2.2.1.1 Body Image

Body Image refers to our subjective experience of the physical structure of our body in terms of its size, shape, and physical composition (Longo, 2016). This dimension was evaluated through both a task, the *Photographic Figure Rating Scale (PFRS) task*, and a questionnaire, the *Body Uneasiness Test (BUT)*.

The PFRS, adapted from the study by Naor-Ziv et al. (Naor-Ziv et al., 2020), was used to assess participants' body image perception and body shape dissatisfaction. From this task, we quantified the following variables: the mean Body Mass Index (BMI) reflecting each participant's actual physique (A), ideal body image (I), and perception of how others perceive their body (O). Furthermore, we calculated the discrepancies between these means and the participants' actual BMI (R), denoted as Δ AR (A-R), Δ IR (I-R), and Δ OR (O-R). These differences provided insights into the participants' levels of misperception regarding their current physique, dissatisfaction with their ideal body image, and inaccurate beliefs about how others view their bodies. BMI R ranged from 17.79 to 34.01 (mean $\pm$ SD: 23.34 ± 3.54); BMI A ranged from 16 to 36 (mean $\pm$ SD: 24.33 ± 4.46); BMI I ranged from 16 to 29.5 (mean $\pm$ SD: 20.41 ± 3.06); BMI O ranged from 16 to 36 (mean $\pm$ SD: 23.70 ± 4.69); Δ AR, as the difference between BMI A and BMI R, ranged from -4.69 to 11.37 (mean $\pm$ SD: 0.93 ± 3.18); Δ IR, as the difference between BMI I and BMI R ranged from -14.51 to 6.62 (mean $\pm$ SD: -2.92 ± 3.08); and Δ OR, as the difference between BMI O and BMI R ranged from -6.37 to 8.87 (mean $\pm$ SD: 0.36 ± 3.35).

The Body Uneasiness Test is a questionnaire designed to assess individuals' attitudes towards their own body image. Developed by Cuzzolaro et al. (Cuzzolaro M, 1999), the BUT (Cuzzolaro et al., 2006; Cuzzolaro & Fassino, 2018; Marano et al., 2007) consists of 34 items and a list of 37 body parts, characteristics, or functions. Participants rate each item on a scale ranging from "Never" (0) to "Always" (5), with higher scores indicating a greater level of impairment or uneasiness. The BUT calculates measures of overall severity and distress related to body uneasiness. These include the Global Severity Index (GSI), defined as BUT A score, and Positive Symptom Total (PST) defined as BUT B.

2.2.1.2 Spatial Tactile Acuity

Spatial Tactile Acuity refers to the ability to precisely perceive the location and quality of touch (Harvie et al., 2018). This dimension was evaluated through the two-point discrimination (2PD) task, which assesses the ability of participants to identify two closely spaced points on a small area of the skin and measures the accuracy of their discrimination skills (Weber, 1996). We compared two body parts chest and thigh used as targets with the neck used as reference (Spitoni et al., 2015). From this task, we quantified the following variables: the correct response for the two target body parts, chest (C-che) and thigh (C-thi); the overestimation for both chest (O-che) and thigh (O-thi) calculated by the errors and overestimation of the body parts compared to the reference and similarly, the underestimation for chest (U-che) and thigh (U-thi) calculated by errors and underestimation of the body parts. The correct responses C-che ranged from 0.5 to 1 (mean $\pm$ SD: 0.77 ± 0.14); the correct responses C-thi ranged from 0.35 to 1 (mean $\pm$ SD: 0.79 ± 0.14). The analysis focused on the measures of underestimation (U-che, U-thi) and overestimation (O-che, O-thi) for each experimental condition (Spitoni et al., 2015) and highlight the importance of considering the body part when examining tactile perception. The underestimation responses U-che ranged from 0 to 0.5 (mean $\pm$ SD: 0.21 ± 0.12); the underestimation responses U-thi ranged from 0.05 to 0.95 (mean $\pm$ SD: 0.45 ± 0.17). The overestimation responses O-che ranged from 0.1 to 1 (mean $\pm$ SD: 0.51 ± 0.22); the underestimation responses O-thi ranged from 0 to 0.85 (mean $\pm$ SD: 0.25 ± 0.20).

2.2.1.3 Body Structural Representation

Body Structural Representation (BSR) refers to knowledge about the topological organization of bodies, outlining how different body parts interrelate within a spatial configuration, focusing on the spatial positioning of each body part related to others (Longo, 2016). This dimension was evaluated through the Finger Localization Task (Benton, 1983), which requires participants to identify and

differentiate stimulated fingers in three different conditions. We focused on the third condition in which participants had to identify which two fingers were simultaneously touched. We calculated the accuracy and included the score of correct responses (HIT) as a variable; the accuracy score ranged from 0.6 to 1 (mean $\pm$ SD: 0.96 ± 0.08).

2.2.1.4 Multisensory Integration

Multisensory Integration refers to the process by which inputs from two or more sensory modalities are combined by the nervous system to form a stable and coherent percept of the world (Yau et al., 2015). This dimension was evaluated through the Multisensory Integration (MSI) task aiming at investigating the integration of visual, auditory, and tactile stimuli in participants' perception. The task focused on evaluating their response speed in relation to the presentation of these stimuli (Dumas et al., 201; Mahoney et al., 2015). For each multisensory pair – audio-visual (av), audio-tactile (at) and visuo-tactile (vt) - the analysis involved calculating the area-under-the-curve (AUC) subtended by the distribution of reaction times to multisensory stimuli as compared to the distribution of reaction times to unimodal stimuli. Hence, AUC-av, AUC-at and AUC-vt represent a proxy of the magnitude of multisensory integration for audio-visual, audio-tactile and visuo-tactile stimuli, respectively (Mahoney, Cotton, & Verghese, 2019). The AUC-AV ranged from 0.001 to 0.66 (mean $\pm$ SD: 0.19 ± 0.18); the AUC-AT ranged from 0.00 to 0.52 (mean $\pm$ SD: 0.15 ± 0.13); the AUC-VT ranged from 0.00 to 0.47 (mean $\pm$ SD: 0.17 ± 0.13).

2.2.1.5 Multisensory Temporal Resolution

Multisensory Temporal Resolution refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. This principle highlights the critical role of temporal proximity in influencing the nervous system's integration of diverse sensory information (Sarko et al., 2012).

This dimension was evaluated through the Simultaneity Judgment (SJ) task, which aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Two parameters are usually derived from this task: the point of subjective equality (PSE), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the 'just noticeable difference' (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed (Binder, 2015). The point of subjective equality (PSE-sj) ranged from -26.18 to 35.00

(mean $\pm$ SD: 0.36 ± 11.08); and the just noticeable difference (JND-sj) ranged from 63.05 to 324.85 (mean $\pm$ SD: 125.01 ± 46.61)

2.2.1.6 Peripersonal Space

Peripersonal Space refers to the space surrounding the body where the integration of stimuli on the body and from the external environment is facilitated (Rabellino et al., 2020).

This dimension was evaluated through the Peripersonal Space (PPS) task (Canzoneri et al., 2012; Di Cosmo, Costantini, Spadone, et al., 2021; Di Cosmo et al., 2018), which allows evaluating the individual's boundaries of the peripersonal space by assessing the optimal temporal interval for the integration of tactile and auditory stimuli (Ferri et al., 2015; Spadone et al., 2021). To this aim, a psychometric function is fitted to the RT data. The PSE of the psychometric function is taken as a proxy of the peripersonal space boundary. PSE values ranged from 300 to 2512.62 (mean $\pm$ SD: 1378.41 ± 474.72), which were used to quantify the boundary of the PPS for each participant.

2.2.1.7 Temporal Tactile Acuity

Temporal Tactile Acuity refers to the ability to perceive and discriminate temporal aspects of tactile stimuli. It involves the capacity to detect and distinguish temporal characteristics of sensations related to touch (Laasonen et al., 2001). This dimension was evaluated through the Temporal Order Judgment. In a typical Temporal-Order Judgment (TOJ) task, participants are tasked with determining the order of two tactile stimuli presented sequentially to their left and right hands. When the hands are in an “uncrossed” position (toju), participants can rely on tactile and proprioceptive cues related to their body posture, utilizing a body-centred reference frame (Heed et al., 2014). From this task, we quantified the JND (JND-toju), as a measure of precision, and the proportion of correct responses (Azañón et al., 2016). The JND-toju represents the smallest interval at which the participants can reliably decide which sensory input of the two presented was first (Kostaki M. & Vatakis A., 2018). The JND (JND-toju) ranged from 6.40 to 202.50 (mean $\pm$ SD: 73.10 ± 41.80).

2.2.1.8 Sensorimotor functions

Touch remapping

To perceive the location of touch in space, the brain combines information about touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands

(Azañón et al., 2016). This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (tojc)(Ferri et al., 2016).

From this task, we measured the following variables: the JND (JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first (Kostaki M. & Vatakis A., 2018) and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions(Ferri et al., 2016). SC-toj is a global indicator of differences, which provides an overarching measure of the divergence between the two conditions and assess increases in judgment reversals resulting from the arm-crossing manipulation (Wada et al., n.d.). The JND (JND-tojc) ranged from 6.47 to 336.47 (mean $\pm$ SD: 96.77 ± 76.10); SC, ranged from -0.02 to 566.94 (mean $\pm$ SD: 117.09 ± 129.21).

Laterality Judgment Task

The Laterality Judgement Task (LJT) is designed to assess participants' ability to mentally rotate the presented hand images and accurately judge the lateral orientation of presented hand images(Mibu et al., 2020). We calculated slopes, which reflect the efficiency of the neural mechanism underlying the mental rotation process: a smaller slope indicates higher neural efficiency in mental rotation(Christova et al., 2008). We quantified slopes for both hands, indicated as Mental Rotation Efficiency for the left hand (MRE-lh) and the right hand (MRE-rh), illustrating the efficiency of the respective mental rotation processes (Ferri et al., 2011). Mental Rotation Efficiency for the left hand (MRE-lh) ranged from 0.52 to 593.83 (mean $\pm$ SD: 248.44 ± 135.17) and the right hand (MRE-rh) ranged from 19.32 to 543.59 (mean $\pm$ SD: 251.64 ± 136.35).

2.2.2 Interoceptive Bodily Dimensions

2.2.2.1 Interoceptive Accuracy

Interoceptive accuracy refers to the accuracy in detecting internal bodily sensations (Garfinkel et al., 2015). Two tasks determined cardiac interoceptive accuracy: the Heartbeat Detection task, also known as the Tapping or Tracking task (Brener & Ring, 2016; McFarland RA., 1975), and the Heartbeat Counting task (R. Schandry, 1981). In the Heartbeat Detection task (d) participants were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared (Fittipaldi et al., 2020; García-

Cordero et al., 2017; Yoris et al., 2017). The Heartbeat Counting task (c) measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats (Koch et al., 2014). The accuracy (Acc-d) ranged from 0.21 to 1 (mean $\pm$ SD: 0.68 ± 0.17) and the accuracy (Acc-c) ranged from 0.18 to 0.98 (mean $\pm$ SD: 0.65 ± 0.18).

2.2.2.2 Interoceptive Sensibility

Interoceptive Sensibility is the subjective account of experiencing internal bodily sensations (Critchley & Garfinkel, 2017). This dimension can be assessed using subjective measures that index both the individual's confidence in their interoceptive ability and their interoceptive feelings (Garfinkel et al., 2015). We evaluated this dimension through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d) and the Heartbeat Counting task (Con-c). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat). The confidence (Con-d) ranged from 1 to 8 (mean $\pm$ SD: 5.11 ± 1.60) and the confidence (Con-c) ranged from 1 to 8.75 (mean $\pm$ SD: 5.67 ± 1.69).

We also used two self-report questionnaires: the Body Perception Questionnaire (BPQ)(Poli, Giovanni, et al., 2021; Porges, 1993) and the Multidimensional Assessment of Interoceptive Awareness (MAIA)(Mehling et al., 2012). The BPQ generally evaluates body awareness and autonomic symptoms. From the BPQ we obtained a score for each subscale: the body awareness (BOA) that consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) that is involved in regulating the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), includes items related to subdiaphragmatic issues. The BOA factor scores ranged from 7 to 21 (mean $\pm$ SD: 15.45 ± 3.40); the SUP factor scores ranged from 8 to 18 (mean $\pm$ SD: 10.36 ± 2.23) and BOA/SUB factor scores ranged from 7 to 21 (mean $\pm$ SD: 13.98 ± 3.04).

The MAIA generally evaluates multiple dimensions of interoception. From the MAIA we obtained a score for each subscale: Noticing (1M), Not-Distracting (2M) Not-Worrying (3M) Attention Regulation (4M) Emotional Awareness (5M) Self-Regulation (6M) Body Listening (7M) Trusting (8M). The (1) Noticing scores ranged from 0.75 to 4.75 (mean $\pm$ SD: 2.9 ± 1.00); (2) Not-distracting scores ranged from 0 to 4.33 (mean $\pm$ SD: 2.22 ± 0.87); (3) Not-worrying scores ranged from 0.33 to 4.33 (mean $\pm$ SD: 2.55 ± 0.98); (4) Attention regulation scores ranged from 0.42 to 5 (mean $\pm$ SD:

3.03 $\pm$ 0.95); (5) Emotional awareness scores ranged from 0.4 to 5 (mean $\pm$ SD: 3.27 $\pm$ 1.04); (6) Self-regulation scores ranged from 0 to 5 (mean $\pm$ SD: 2.55 $\pm$ 1.23); (7) Body listening scores ranged from 0 to 4.66 (mean $\pm$ SD: 2.74 $\pm$ 1.18) and (8) Trusting scores ranged from 0.66 to 5 (mean $\pm$ SD: 3.34 $\pm$ 1.09).

2.2.2.3. Interoceptive Awareness

Interoceptive Awareness is the metacognitive awareness of interoceptive accuracy and refers to the correspondence between objective interoceptive accuracy and subjective confidence report (Garfinkel et al., 2015; Suzuki et al., 2013). We quantified the participant's awareness by comparing the accuracy and the sensibility in both the Heartbeat Detection task (Aw-d) and the Heartbeat Counting task (Aw-c). The awareness (Aw-d) ranged from 0.07 to 0.99 (mean $\pm$ SD: 0.77 $\pm$ 0.17) and the awareness (Aw-c) ranged from 0.52 to 0.93 (mean $\pm$ SD: 0.76 $\pm$ 0.11).

2.3. Statistical Analysis: Machine Learning Approach

When attempting to predict an output based on input that may be correlated with each other, the high collinearity among features, combined with the high number of features compared to the number of samples (such as subjects or tests in our case), can potentially disrupt the results, leading to unstable predictions that are sensitive to noise and susceptible to overfitting and poor generalization. Various linear and nonlinear regression and classification algorithms have been created to avoid the issue of overfitting. These methods can employ different approaches, including penalizing the fitting parameter through techniques like regularization or reducing the dimensionality of the feature space to mitigate overfitting. In this study, a linear regression analysis was conducted using a technique that involves reducing the dimensionality of the feature space, namely the Partial Least Square Regression (PLSR). PLSR has been widely demonstrated to be successful in mitigating overfitting, especially when dealing with collinearity. PLSR is based on the fundamental assumption that the observed data is produced by a system or process influenced by a limited number of latent variables that are not directly observed or measured. PLSR enables the creation of regression equations by condensing the predictors into a more concise set of uncorrelated components, which are linear combinations of the initial predictors. This approach conducts regression on these components, identifying those that capture the most pertinent information within the independent variables. This aids in predicting the dependent variable while simultaneously reducing the complexity of the regression problem by employing a smaller number of components than the original count of independent variables. PLSR can be viewed as a supervised learning method, a sort of supervised Principal Component Analysis.

In contrast to PCA, which reduces the dimensionality of the feature space by analysing the eigen solutions of the covariance matrix in an unsupervised manner, PLSR is a supervised learning algorithm. PLSR achieves this by determining feature space components that maximize the covariance between the independent and dependent variables, making it another form of supervised learning algorithm. The PLSR algorithm necessitates an a priori selection of one parameter, known as a hyperparameter, i.e., the number of uncorrelated components (K) to be used for regression. Generally, to conduct hyperparameter optimization, a training set, a validation set, and a test set are required. The training set is used to train the algorithm (e.g., estimate PLSR weights), the validation set is used to optimize the hyperparameter (e.g., estimate the optimal K), and the test set is used to assess the generalization performance of the learning process. This separation of data implies a reduced sample size as part of a trade-off choice among the sets.

Furthermore, another approach that minimizes the loss of samples in the different sets while evaluating the algorithm's generalization capabilities is cross-validation (CV). In CV, the data is divided into folds, and the model is trained on all data except one-fold in an iterative manner. The out-of-sample performance (i.e., generalization) is assessed based on the remaining fold and averaged across iterations. If the number of folds equals the number of samples, which is often referred to as "leave-one-out" cross-validation, it provides a rigorous assessment of the model's generalization performance. If the hyperparameters of the model need to be optimized, the optimization process cannot be reliably determined based on a simple CV without sacrificing a generalizable estimate of model performance. CV can be adapted to simultaneously select the best set of hyperparameters and provide a generalizable error estimation through a procedure called nested CV. Starting with k folds, nested cross-validation (nCV) is performed with an outer loop of k folds and an inner loop of $k-1$ folds. The outer loop estimates the generalization performance of the model (i.e., test), while the inner loop evaluates the optimal hyperparameters (i.e., validation).

In each iteration, a fold is selected as the outer set (for assessing generalization), and the remaining $k-1$ sets are combined to form the corresponding outer training set. Then, each outer training set is further subdivided into j sets, and one set is iteratively chosen as the inner test set (for evaluating the optimal hyperparameters), with the $j-1$ other sets forming the corresponding inner training set.

If the number of folds equals the number of samples for both loops, the procedure is referred to as leave-one-out nCV. In this study, a leave-one-out nCV was implemented to assess the PLSR generalization performance and the optimal number of components using the following variables as the dependent variables: SPQ-Cognitive-Perceptual (SPQ-CP), SPQ-Interpersonal (SPQ-I), SPQ-Disorganization (SPQ-D) and SPQ-Total (SPQ-TOT). For each of them, PLSR was used to test three

models, each of which used exteroceptive, interoceptive, and intero-exteroceptive variables (BMI (R), A (actual), I (ideal), O (other), Δ AR, Δ IR, Δ OR, Pt. tot. A, Pt. tot. B, C-che, O-che, U-che, U-thi, O-thi, C-thi, HIT, AUC-av, AUC-at, AUC-vt, PSE-sj, JND-sj, PSE-pps, JND-toju, JND-tojc, SC-toj MRE-lh, MRE-rh, Acc-d, Acc-c, Con-d, Con-c, BOA, SUP, BOA/SUB, 1M-8M, Aw-d, Aw-c) as independent variables, described in table 1, resulting in a total of 12 models. Each model was trained and tested separately.

The regression performances of the models were evaluated through correlation analyses between the predicted values and the actual values (which likely stand for some specific variable or outcome). The correlation coefficient, denoted as "r," is reported for each tested model. The degrees of freedom (DF) and the significance of the null hypothesis (p) are also reported in the analysis. These values help assess the strength and significance of the correlations between the predicted and actual values.

Furthermore, the statistical significance of the weights was assessed using a randomization procedure, which involved constructing a confidence interval for the null hypothesis of each weight being zero (iterating the same algorithm 10^6 times on random shuffled outcomes).

3. Results

3.1 Contribution of exteroceptive bodily dimension to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by the exteroceptive dimensions of body representations, we ran three models, one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and Disorganization (SPQ-D). Furthermore, to explore the role of exteroceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of exteroceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was significant after cross-validation. A significant positive correlation between the actual SPQ-CP and the predicted SPQ-CP was obtained ($r = 0.594$, $p < 0.001$). Dimensions that significantly contributed were: body image (BUT-A, BUT-B, Δ AR), spatial tactile acuity (C-che, C-thi, U-che, O-che, U-thi), body structural representation (HIT), multisensory temporal resolution (JND-sj) and sensorimotor functions (MRE-lh, JND-tojc, SC-toj) (see figure 1a).

The model testing the predictive impact of exteroceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.559$, $p < 0.001$). Dimensions that

significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, C-thi, O-che), body structural representation (HIT), multisensory integration (AUC-at) peripersonal space (PSE-sj) and sensorimotor functions (MRE-lh) (see figure 1b).

The model testing the predictive impact of exteroceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.501$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, O-che, U-thi), body structural representation (HIT), and sensorimotor functions (MRE-lh) (see figure 1c).

The model testing the predictive impact of exteroceptive bodily dimensions on total schizotypy (SPQ-TOT) was significant after cross-validation. A significant positive correlation between the actual SPQ-TOT and the predicted SPQ-TOT was obtained ($r = 0.699$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, O-che), body structural representation (HIT), and sensorimotor functions (MRE-rh, MRE-lh) (see figure 1d).

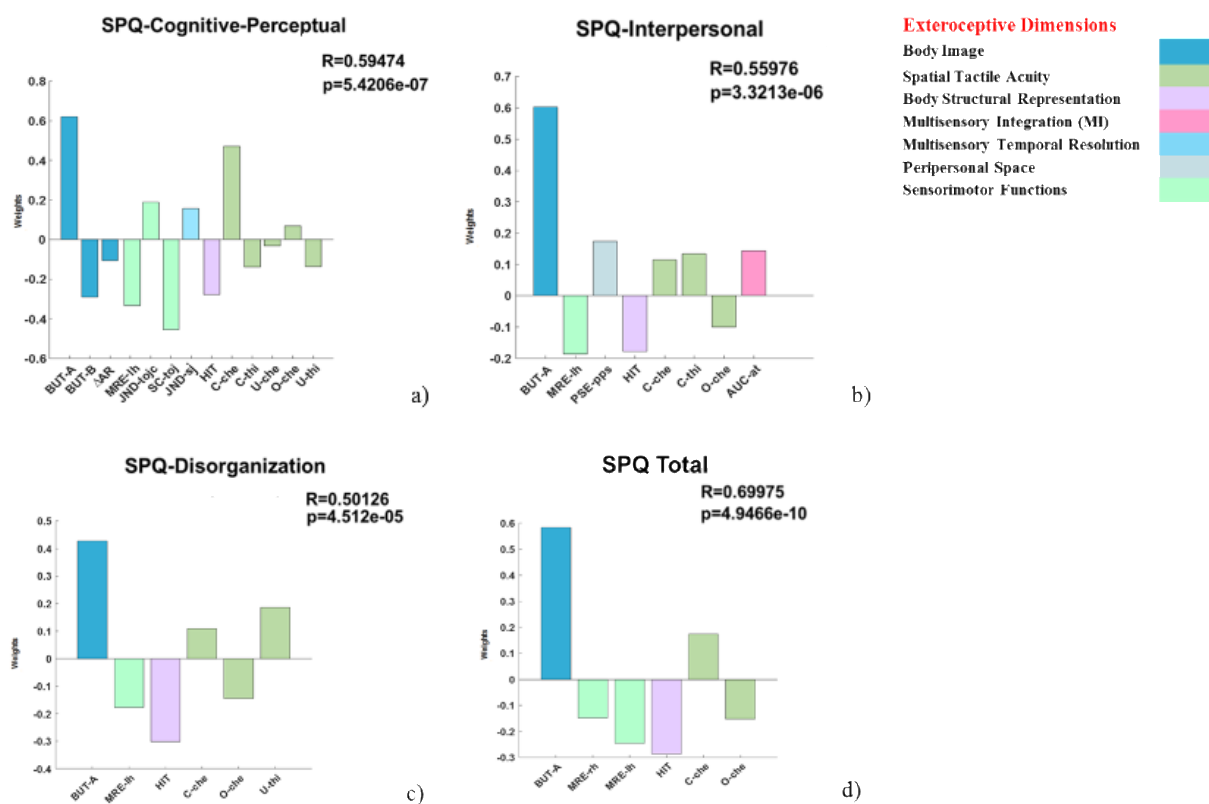


Figure 1. Contribution of exteroceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). a) SPQ-CP:

Regression weights for exteroceptive variables (BUT A, BUT-B, MRE-lh, JND-sj, JND-tojc, SC-toj, Δ AR, HIT, C-che, C-thi, U-che, O-che, U-thi). b) SPQ-I: Weights for variables (BUT A, MRE-lh, PSE-pps, HIT, C-che, C-thi, O-che, AUC-at). c) SPQ-D: Weights for variables (BUT A, MRE-lh, HIT, C-che, O-che, U-thi). d) SPQ TOT: Weights for variables (BUT A, MRE-rh, MRE-lh, HIT, C-che, O-che). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

3.2 Contribution of interoceptive bodily dimension to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by the interoceptive dimensions of body representations, we ran three models one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and Disorganization (SPQ-D). Furthermore, to explore the role of interoceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of interoceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was non-significant after cross-validation.

The model testing the predictive impact of interoceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.388$, $p < 0.001$). Dimensions that significantly contributed were: interoceptive accuracy (Acc-c) and interoceptive sensibility (3M, 4M, 5M, 8M, BPQ-SUP, Con-d, Con-c) (see figure 2a).

The model testing the predictive impact of interoceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.488$, $p < 0.001$). The dimension that significantly contributed was interoceptive sensibility (8M, BPQ-SUP) (see figure 2b).

The model testing the predictive impact of interoceptive bodily dimensions on total schizotypy (SPQ-TOT) was non-significant after cross-validation.

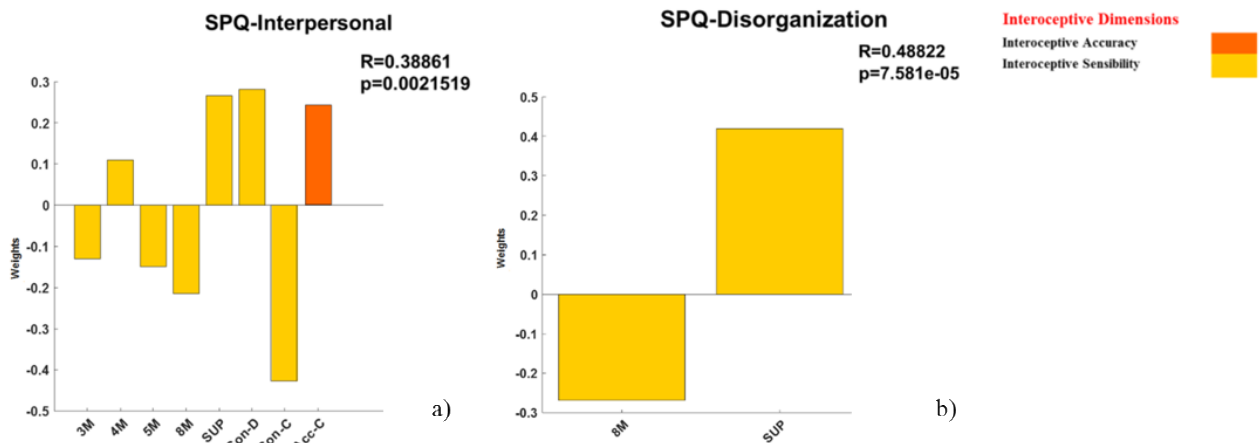


Figure 2. Contribution of interoceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). a) SPQ-I: Regression weights for interoceptive variables (3M, 4M, 5M, 8M, BPQ-SUP, Con-d, Acc-c, Con-c). b) SPQ-D: Regression weights for interoceptive variables (8M, BPQ-SUP). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

3.3 Contribution of both exteroceptive and interoceptive bodily dimensions to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by both the exteroceptive and interoceptive dimensions of body representations, we ran three models one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and Disorganization (SPQ-D). Furthermore, to explore the role of both exteroceptive and interoceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was non-significant after cross-validation.

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.481$, $p < 0.001$). Dimensions that significantly contributed were: body image (BUT-A, BUT-B), spatial tactile acuity (C-che), body structural representation (HIT), peripersonal space (PSE-sj), interoceptive accuracy (Acc-c) and interoceptive sensibility (5M, 8M, BPQ-SUP, Con-d, Con-c) (see figure 3a).

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant

positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.525$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A) and interoceptive sensibility (BPQ-SUP) (see figure 3b).

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on total schizotypy (SPQ-TOT) was non-significant after cross-validation.

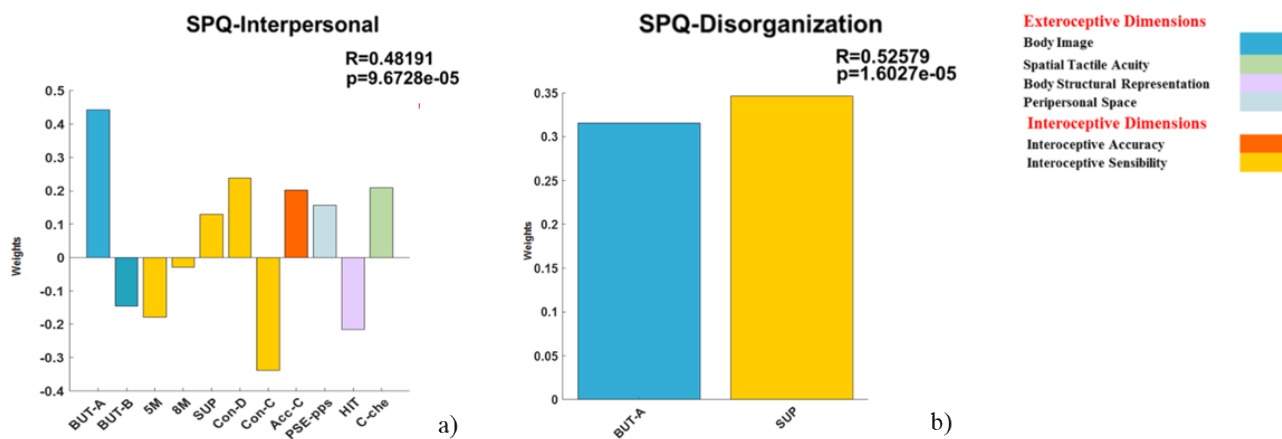


Figure 3. Contribution of both exteroceptive and interoceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). a) SPQ-I: Regression weights for exteroceptive and interoceptive variables (BUT A, BUT-B, 5M, 8M, BPQ-SUP, Con-d, Acc-d, Con-c, PSE-pps, HIT, C-che). b) SPQ-D: Weights for variables (BUT A, BPQ-SUP). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

4. Discussion

In this study, we investigated the potential contribution of exteroceptive and interoceptive bodily dimensions to schizotypal personality traits, such as the cognitive-perceptual trait representing positive-like symptoms of schizophrenia, the interpersonal trait representing the negative-like symptoms, and the disorganization trait representing disorganized-like symptoms. For each schizotypal personality trait, we determined the contribution of exteroceptive and interoceptive bodily dimensions separately and in combination. To this aim, we employed Partial Least Squares Regression (PLSR). This method allowed us to integrate several bodily dimensions to understand their impact on schizotypy, revealing specific and non-specific contributions of exteroceptive and interoceptive dimensions to different traits, as shown in Table 2.

Table 2 Specific and non-specific contributions of exteroceptive and interoceptive dimensions to different schizotypal traits

	Cognitive-Perceptual	Interpersonal	Disorganization	Total SPQ
Exteroception	Body Image Spatial tactile acuity Body structural representation Multisensory Temporal Resolution Sensorimotor functions	Body Image Spatial tactile acuity Body structural representation Multisensory Integration (MI) Peripersonal space Sensorimotor functions	Body Image Spatial tactile acuity Body structural representation Sensorimotor functions	Body Image Spatial tactile acuity Body structural representation Sensorimotor functions
Interoception		Interoceptive Accuracy Interoceptive Sensibility	Interoceptive Sensibility	
Exteroception and Interoception		Body Image Spatial tactile acuity Body structural representation Peripersonal space Interoceptive Accuracy Interoceptive Sensibility	Body Image Interoceptive Sensibility	

These results make a novel and significant contribution to the literature. By employing a predictive, multimodal approach that simultaneously tests multiple bodily dimensions, rather than analysing them individually, we were able to account for compensatory or synergistic interactions between bodily dimensions. For the first time, this methodology allowed us to predict the specific contribution of bodily experiences to schizotypy, revealing distinct patterns of influence for each trait that had not been previously explored. Furthermore, we were able to assess the specific roles of exteroceptive and interoceptive dimensions in schizotypal traits, enhancing our understanding of their respective contributions to the risk of developing psychosis along the schizophrenia continuum.

4.1 Contributions of bodily dimensions to cognitive-perceptual traits

Our findings suggest that altered temporal sensitivity to multisensory stimuli is a specific contribution to cognitive-perceptual traits (Di Cosmo, Costantini, Ambrosini, et al., 2021). This result is supported by previous literature indicating impairments in the temporal aspects of multisensory integration among individuals with schizophrenia across various sensory domains. Previous studies show that patients with schizophrenia exhibit deficits in integrating audiovisual stimuli, highlighting the importance of multisensory integration in perceptual and cognitive processes (Tseng et al., 2015). Furthermore, research indicates that these deficits are not limited to the integration of external inputs, such as auditory and visual information from the environment, but also extend to the processing of somatosensory stimuli and their synchronization with external stimuli, that is, audio tactile stimuli (Di Cosmo, Costantini, Ambrosini, et al., 2021). Additional reports show reduced temporal sensitivity

of sensory processing and increased tolerance to asynchronies in both high schizotypy (Ferri et al., 2017) and schizophrenia (Nikulin et al., 2012), reflecting abnormal temporal dynamics of neural activity. These findings suggest that abnormalities related to the temporal aspects of multisensory integration, including lengthened simultaneity ranges for auditory stimuli in schizophrenia (Foucher et al., 2007), may contribute to positive symptoms such as auditory or visual hallucinations.

4.2 Contributions of bodily dimensions to interpersonal traits

Our results show that peripersonal space is a specific predictor of interpersonal traits, representing the negative-like symptoms. These results are consistent with prior studies that provided evidence linking the extension of peripersonal space to negative symptoms but not to positive symptoms in patients with schizophrenia (Holt et al., 2015; Park et al., 2008) and in individuals with high schizotypy (Di Cosmo et al., 2018). In these studies, (Di Cosmo et al., 2018; Park et al., 2008) peripersonal space was measured using a multisensory task (Canzoneri et al., 2012) in which the peripersonal space mapping is allowed through the integration of visual or auditory and somatosensory information (Serino, 2019). Consistent with this, another specific predictor of interpersonal traits is multisensory integration.

In agreement with the association between PPS extension and interoceptive accuracy shown in healthy individuals (Ardizzi & Ferri, 2018), we found that interoceptive dimensions that significantly predicted interpersonal traits were interoceptive accuracy and interoceptive sensibility. Few recent literatures focused on interoception in individuals with schizotypal personality traits (Torregrossa et al., 2022) and schizophrenia (Ardizzi et al., 2016; Koreki et al., 2021) and the relationship between interoception and schizophrenia remains complex and not fully elucidated. While studies focusing on patients with schizophrenia consistently report lower interoceptive accuracy (Ardizzi et al., 2016; Critchley et al., 2023; Koreki et al., 2021; Torregrossa et al., 2022) and alterations in interoceptive sensibility (Koreki et al., 2021; Torregrossa et al., 2022) the nature of these differences and their relationship with clinical symptoms are still under debate. For instance, some studies mentioned before, suggested a potential association between interoceptive accuracy and symptom severity, with better interoceptive accuracy linked to more severe positive symptoms (Ardizzi et al., 2016), while another, found associations with both positive and negative symptoms (Koreki et al., 2021), and a third reported no significant relationship between symptoms and interoceptive measures (Torregrossa et al., 2022). Furthermore, a study that investigated the association between interoception and schizotypy found no significant associations (Torregrossa et al., 2022). However, for the first time, our results suggest a specific link between interoceptive dimensions and interpersonal traits or negative-like symptoms in schizotypy. These differences in results may regard various

methodological and contextual factors, for example, the use of different SPQ questionnaire versions (Torregrossa et al., 2022). Additionally, the initial signs of schizophrenia typically manifest as negative symptoms (Jauhar et al., 2022), gradually intensifying until the onset of the first episode, followed by the emergence of positive symptoms (Häfner et al., 1998). Considering the link between interoception and the affective domains (Barrett, 2017; Feldman et al., 2024), and that negative symptoms mark the onset of the illness, it is conceivable that alterations in interoception may already be present within the subclinical population. However, this does not mean that interoceptive disruptions will not eventually affect cognitive symptoms as well. According to the somatic marker hypothesis (A. Damasio & Carvalho, 2013; A. R. Damasio, 1996) bodily signals, including interoceptive feedback, are crucial for both decision-making (Y. Lee et al., 2007) and emotional regulation (Kim et al., 2019). Disruptions in interoceptive processing may therefore contribute not only to the social and emotional difficulties observed in both schizotypy (Torregrossa et al., 2023; Uono et al., 2021) and schizophrenia (Y. Lee et al., 2007; Yao & Thakkar, 2022), but also to the impairments in emotion-based decision-making commonly seen in patients with schizophrenia (Sevy et al., 2007).

4.3 Contributions of bodily dimensions to disorganization traits

Our results show no specific contribution for disorganization traits. According to the multidimensional model of schizophrenia, disorganization is considered a basic psychopathological dimension, together with positive and negative symptoms. While the DSM-V primarily captures disorganization in terms of language and behaviour, disorganization is also linked to early onset of schizophrenia, a family history of psychosis, and low levels of insight and treatment compliance (Nestsiarovich et al., 2017). Moreover, recent studies demonstrate that in first-episode schizophrenia patients, disorganization is associated both with positive and negative symptoms (Pelizza et al., 2021). However, disorganization has been less extensively studied with respect to the positive and negative dimensions, especially in the prodromal phases of schizophrenia, and thus warrants further investigation and the development of more specific tools to assess this dimension in schizotypy. The absence of specific exteroceptive and interoceptive contributions to disorganization traits in our study may reflect a limitation of the tests used, which may not fully address aspects of body representation linked to disorganization symptoms. Alternatively, disorganized symptoms may be more strongly related to other risk indices for schizophrenia, such as cognitive deficits, which can be assessed using cognitive batteries (Levaux et al., 2007).

Previous studies have shown that cognitive deficits in areas like working memory, attention, and executive functioning are strongly associated with disorganized symptoms (Barnett et al., 2010;

Leeson et al., 2009) and can predict long-term functional outcomes (Leeson et al., 2009). Our findings add to this by suggesting that exteroceptive alterations are specifically linked to cognitive-perceptual (positive-like) traits, while interoceptive alterations are associated with interpersonal (negative-like) traits in schizotypy.

This pattern indicates that bodily experiences may play a primary role in the positive and negative symptom domains, while disorganization is more closely related to cognitive functions. Consistent with this, network analyses have found that cognitive scores are distinct from positive and negative symptoms, although they are associated with disorganization (Chang et al., 2020; Moura et al., 2021). This distinction supports the idea that, while bodily dimensions may contribute mainly to positive and negative traits, disorganized symptoms are likely to reflect underlying cognitive deficits, which could explain the lack of specific contributions to disorganization traits in our study.

4.4 Non-specific contributions to schizotypal traits

Our results show that, among the interoceptive and exteroceptive bodily dimensions we tested, non-specific contributions to schizotypal traits, that is bodily dimensions that predicted all traits of schizotypy, came only from some exteroceptive dimensions, such as body image, spatial tactile acuity, body structural representation, and sensorimotor functions. The contributions of these exteroceptive dimensions suggest that these dimensions are common across schizotypal traits. Consistent with our results on spatial tactile acuity, previous studies have detected an association between two-point discrimination thresholds and schizotypal features (Lenzenweger, 2000). Moreover, other studies have found that anomalies in body image (Priebe & Röhrlich, 2001) and abnormal sensorimotor representations (Ardizzi et al., 2020) are common features of schizophrenia spectrum disorders and are observable also in schizotypy, significantly before the onset of the first schizophrenia symptoms occur (Handest & Parnas, 2005). Our findings are also in line with the observation from several studies indicating impairments in body structural representation (Graham-Schmidt et al., 2016) both in patients with schizophrenia (Costantini et al., 2020) and individuals with high levels of schizotypy (Fotia et al., 2022). The identified exteroceptive dimensions seem to characterize the schizotypal construct, suggesting their basic role across all schizotypal personality traits. These same dimensions are also significant predictors of the total SPQ score, further confirming their essential contribution to the overall schizotypy.

Regarding interoceptive dimensions, interoceptive sensibility was found to contribute to both interpersonal and disorganized traits, further supporting the somatic marker hypothesis by highlighting the potential role of interoceptive deficits in impairments of emotional regulation and emotion-based decision-making (Gallagher, 2005; Varela et al., 1993), which are commonly

observed in patients with schizophrenia. Overall, our results support the phenomenological psychopathology and embodied neuroscience perspectives, which suggest that a core feature of the schizophrenia spectrum is abnormalities in fundamental selfhood, or ‘ipseity’(Gallagher, 2004; Nordgaard & Parnas, 2014). This pre-reflective sense of self is likely grounded in the body, which subtly influences cognition without explicit conceptualization(De Haan & Fuchs, 2010). The body thus provides a tacit, background sense of first-person presence, grounding the relationship between self and environment (Gallese & Ferri, 2013; Petitmengin et al., 2019; Uhlhaas & Mishara, 2006).

4.5 Limitations and future directions

Our study provides valuable insights into the relationship between interoception and schizotypy, though some limitations should be noted. To thoroughly assess interoception, we employed two distinct cardiac tasks: the heartbeat detection task and the heartbeat counting task. Although the heartbeat counting task has raised concerns regarding its validity as a measure of interoceptive accuracy (e.g.,Desmedt et al., 2022; Zamariola et al., 2018), it remains one of the most widely used tools in interoception research, particularly in studies on schizophrenia and schizotypy (e.g.,Ardizzi et al., 2016; Critchley et al., 2019; Koreki et al., 2021; Torregrossa et al., 2022). To enhance the robustness of our assessment, we also included the heartbeat detection task as a complementary measure, providing a more comprehensive evaluation of cardiac interoception. Nonetheless, interoception research is still in its infancy, and our reliance on these tasks reflects this developmental phase in the field.

Additionally, while our study primarily focused on cardiac interoception, we recognize that interoception encompasses a broad array of physiological signals, including those related to the gastrointestinal, respiratory, and proprioceptive systems (Correll & Schooler, 2020). These other domains may play an important role in understanding the full scope of interoceptive processing in schizophrenia.

Looking forward, there is significant potential for improving our understanding of interoception in both schizotypy and schizophrenia. Future research should refine cardiac interoceptive tasks and consider expanding beyond cardiac signals to include other interoceptive domains, such as respiratory signals. A more comprehensive approach to interoception could lead to a more nuanced understanding of interoceptive processing, with important implications for both clinical and non-clinical populations.

Overall, our study brings to light two key observations. Firstly, while exteroceptive dimensions contribute to all aspects of schizotypy, interoceptive dimensions only show a contribution to

interpersonal and disorganized traits, commonly occurring during the prodromal phase of schizophrenia and preceding the onset of positive symptoms (Correll & Schooler, 2020). This association may stem from the putative role of interoception in fostering the stability of the bodily minimal self, contrasting with the ever-changing nature of exteroceptive information (Tsakiris, 2017). Consequently, early interoceptive deficits may let exteroceptive information, including those related to the body, undermine the minimal self. Secondly, our work highlights the importance of exploring the role of bodily dimensions to identifying both specific and non-specific therapeutic intervention targets. Particularly, interoception emerges as a potential prodromal marker, suggesting that early intervention aimed at enhancing interoceptive processing could be crucial for developing tailored treatments. By identifying specific deficits in interoception and exteroception, our work not only enhances our understanding of the bodily dimensions underlying schizotypal traits but also has significant clinical implications. It opens the door to symptom-specific therapeutic approaches, such as tool-based (Ferroni et al., 2022) or multisensory-based (Serino et al., 2015) training to improve peripersonal space, as well as virtual reality technologies (Novo et al., 2021) designed to enhance bodily self-awareness. Additionally, specialized interoceptive training programs - such as heartbeat perception training (Schaefer et al., 2014; Schillings et al., 2022) - could help improve interoceptive accuracy. However, further research is needed to evaluate the effectiveness of these interventions in individuals with high schizotypy and in patients with schizophrenia.

CHAPTER 3.

Interoceptive and exteroceptive contributions to clinical condition: a comparison between anxiety and depression

1. Introduction

Anxiety and depression are two of the most widespread mental health conditions, recognized as leading contributors to the global burden of disease (World Health Organization, 2022). Together, they affect over 300 million people worldwide, with significant implications for individual well-being, societal productivity, and healthcare costs (Liu et al., 2024). Despite being distinct disorders, they often co-occur, sharing common pathways of emotional dysregulation, cognitive impairments, and physiological alterations (Kircanski et al., 2016). This comorbidity highlights the importance of developing tailored strategies to explore both the overlapping and distinct physiological and psychological pathways involved.

According to the proposed framework (Abend, 2023; Rosen & Schulkin, 1998), pathological anxiety is characterized by an exaggerated expression of normative defensive responses, manifesting as heightened vigilance, persistent worry, and an amplified perception of threat (American Psychiatric Association, 2013; Kenwood et al., 2021). On a physiological level, this heightened state of reactivity manifests as increased heart rate, muscle tension, and other somatic symptoms (Oexle & Reuster, 2023), which in turn amplify the experience of anxiety (Paulus & Stein, 2006). Conversely, depression is a mood disorder characterized by pervasive feelings of sadness, anhedonia, and a diminished capacity to experience pleasure (Chand & Arif, 2023; *ICD-10 : International Statistical Classification of Diseases and Related Health Problems : Tenth Revision*, 2003) alongside neurovegetative symptoms, such as changes in sleep patterns, appetite, and energy levels that further contribute to its debilitating impact (“Depression. Clinical, Experimental and Theoretical Aspects,” 1969). Depression is also associated with autonomic dysfunction, manifesting as reduced heart rate variability (Dawson et al., 1977; Quadt et al., 2018).

One emerging area of interest is the role of bodily awareness in these disorders (Orphanidou et al., 2023) particularly through the dimensions of interoception defined as the perception of internal bodily states (A. D. Craig, 2002), and the processing of external sensory stimuli. Anxiety and depression are increasingly viewed not only as disorders of cognition and emotion but also as conditions rooted in disrupted bodily processing (Jenkinson et al., 2024; Paulus & Stein, 2010; Quadt et al., 2018). Recent

theoretical and phenomenological perspectives emphasize that anxiety and depression are deeply rooted in bodily experience.

In anxiety, bodily hypervigilance and heightened interoception awareness contribute to persistent distress, reinforcing maladaptive cycles of physiological arousal and worry (Orphanidou et al., 2023). The misalignment of interoceptive processing may play a significant role in the development of anxiety disorders, as the misattribution of bodily sensations has been identified as a key factor in the onset of panic and related anxiety symptoms (Clark et al., 1997). Individuals with a heightened tendency to focus the attention on internal body signals tend to detect internal physiological changes more readily, which may contribute to excessive bodily vigilance and symptom exacerbation. Hence, several studies show that higher interoceptive accuracy is related to higher anxiety traits (Saltafossi et al., 2025; Tsakiris & De Preester, 2018). Studies have found that interoceptive sensibility (i.e., self-report measures of interoception) is elevated in individuals with a variety of anxiety related conditions (Ehlers & Breuer, 1992; Näring & van der Staak, 1995). In accordance with this, interoceptive accuracy is also frequently elevated in individuals with anxiety, indexed by heightened performance on heartbeat perception tests in patients with anxiety and elevated occurrence of trait anxiety symptoms (Pollatos et al., 2007).

Depression has been described as a condition where bodily transparency is lost (Fuchs & Schlimme, 2009), leading individuals to experience their body as heavy, rigid, and disconnected from daily functioning. Moreover, the phenomenological perspective highlights the shift from the "feeling body" (noetic) to the "felt body" (noematic), suggesting that depression fundamentally alters how a person perceives and interacts with the world (Ratcliffe, 2014). In depressive states, the body is no longer experienced as a seamless medium for action but rather as an obstacle (Fuchs, 2005). This transformation contributes to social withdrawal and a diminished ability for affective resonance, further intensifying feelings of detachment and isolation (Svenaeus, 2014). In severe cases, bodily sensations of numbness or heaviness are linked to a fading sense of self (Rhodes et al., 2019).

Depression is also associated with autonomic dysfunction, manifesting as reduced heart rate variability (Dawson et al., 1977; Quadt et al., 2018). The role of interoception in low mood and clinical depression has been also investigated in several studies. Research suggests that interoceptive accuracy is reduced in low to moderate, but not severe depression (Dunn et al., 2007). Furthermore, a negative correlation between heartbeat perception and depressive symptoms has been reported (Pollatos et al., 2009), indicating that individuals with lower interoceptive accuracy may experience emotions with diminished intensity. Moreover, studies on healthy controls demonstrate a correlation between interoceptive accuracy and intensity of experienced emotions, where better accuracy

correlates with reports of more intense feelings (Wiens et al., 2000), raising the possibility of an impairment in interoceptive accuracy in depression where emotional “numbness” is often reported (Quadt et al., 2018).

Increasing evidence suggests that alterations in exteroceptive processing also contribute to anxiety and depression. For instance, anxiety and fear can result in changes in the perception of the external environment (Lee et al., 2024). This is particularly relevant for the peripersonal space (PPS) dimension, the immediate area surrounding the body where interactions with objects and others occur (Serino, 2019a). PPS is dynamically shaped by multisensory integration and serves both defensive and social functions. Research indicates that trait anxiety is associated with an expanded PPS, meaning that anxious individuals perceive threats as closer than they are, reinforcing hypervigilance and avoidance behaviours (Iachini et al., 2015; Sambo & Iannetti, 2013). This suggests that anxiety alters spatial perception in a way that prioritizes self-protection by extending the body's safety margin (Iachini et al., 2015). Furthermore, threatening stimuli appear to distort perceptual space and time, leading to an overestimation of the proximity of danger and a misinterpretation of environmental cues (Lee et al., 2024; McNaughton & Corr, 2004). These findings suggest that anxiety can lead to perceptual aberrations, including mis-estimation of space and time (Vagnoni et al., 2012, 2015). No study has investigated PPS in depression. Disruptions in space and time perception observed in anxiety may reflect broader alterations in multisensory integration (Lee et al., 2024; Vagnoni et al., 2012, 2015). Although direct evidence on anxiety and depression remains limited, it is well-documented that multisensory processes are fundamentally involved in bodily self-consciousness (Aspell et al., 2012) and emotion regulation, that are often altered in both anxiety and depression (Quadt et al., 2018).

Body image integrates perceptual, conceptual, and emotional aspects of bodily awareness (de Vignemont, 2010; Pitron et al., 2018; Sattin et al., 2023). According to Longo (Longo, 2016) body image refers to our subjective experience of the physical structure of our body and encompasses all explicit and cognitive-affective representations of the body, including its shape, size, and aesthetic perception while Cash (Cash, 2004) defines body image as a person's body-related self-perceptions and self-attitudes, including body-related thoughts, feelings, and behaviours. The concept of body image includes at least two components: perceptual body size (i.e., estimation of one's body size, which can be distorted when different from actual body size) and attitudinal body image (i.e., affective, cognitive, and behavioural concerns with one's body size) (Paans et al., 2018). Growing evidence suggests that body image disturbances may also play a role in affective disorders. In individuals with depression, the body image influences how they relate to themselves and their environment, typically they experience low energy, discomfort in the body during social interaction,

and a tendency to distance oneself from sensing the body (Pylvänäinen et al., 2021). Major depressive disorder and high depressive symptoms are associated with higher body image dissatisfaction and to a larger perceptual body size (Paans et al., 2018).

In relation to anxiety, body image has been primarily investigated in adolescent populations (e.g. Dou et al., 2023; Vannucci & Ohannessian, 2017), it is considered as a central aspect in the development of emotional and social difficulties. Anxiety, particularly social anxiety, has been consistently linked to increased body-related dissatisfaction, which may contribute to distortions in body image perception (Dou et al., 2023). Findings suggest that body image dissatisfaction is associated with concurrent symptoms of multiple anxiety disorders (Vannucci & Ohannessian, 2017).

However, despite the focus of previous research on body image and peripersonal space, other bodily dimensions such as spatial tactile acuity, body structural representation, multisensory integration, multisensory temporal resolution, temporal tactile acuity and sensorimotor functions, have rarely been investigated in anxiety and depression. We included these dimensions based on evidence from alteration in other clinical population (e.g. Fotia et al., 2022; Costantini et al., 2020; Ardizzi et al., 2020) and are involved in embodied models of self. From this perspective, disruptions in the integration of bodily signals, both internal and external, could contribute to anxiety and depression even if not yet systematically studied. Based on this rationale, the present study adopted a broader and exploratory perspective, including a comprehensive set of bodily dimensions to identify novel predictors of anxiety and depression.

The present study aimed to explore how interoceptive and exteroceptive bodily dimensions contributed to anxiety and depression and explore both the overlapping and distinct contribution. To this aim, we administered a behavioural battery designed to assess multiple aspects of body representation, including body image, spatial tactile acuity, body structural representation, multisensory integration, multisensory temporal resolution, peripersonal space, temporal tactile acuity and sensorimotor functions, and interoceptive accuracy, interoceptive sensibility and interoceptive awareness (Pasciucco et al., 2025). Theoretical perspectives from embodied cognition and the role of interoception on the development of the self (Musculus et al., 2021; Varela et al., 1993) emphasize that perception, emotion, and self-experience are continuously shaped by integrated exteroceptive, interoceptive and multisensory aspects that together create a unified experience of "being in the body." Hence, the dimensions included in the battery assess distinct but interacting bodily dimensions. With the inclusion of both interoceptive and exteroceptive measures, we aimed to investigate whether and which bodily dimensions predict anxiety and depression, and to highlight the common and/or distinct bodily predictors. To this end, we employed Partial Least Squares Regression

(PLSR), a multivariate supervised learning approach particularly suited for handling collinear predictors and high-dimensional data. This data-driven method enabled us to assess how specific configurations of bodily processing differentially predict anxiety and depression symptoms, while accounting for interdependencies among bodily dimensions.

2. Methods and materials

2.1. Participants

Sixty healthy, right-handed volunteers (36 females, mean age $\pm$ SD: 25.71 ± 5.47 years) participated in the study after providing written informed consent. Recruitment was conducted through an online questionnaire. Eligibility criteria required the absence of neurological, psychiatric, or general medical conditions, as well as no family history of psychosis. The experimental protocol was approved by the Institutional Ethics Committee at the University G. d'Annunzio, Chieti-Pescara. All participants completed assessments for anxiety and depression symptoms using validated questionnaires.

2.1.2 State-Trait Anxiety Inventory (STAI-T)

The State-Trait Anxiety Inventory (Spielberger, 1989) is a self-report questionnaire that utilizes a Likert scale ranging from 1 to 4 (with 1 = not at all and 4 = very much). The inventory is comprised of two subscales which assesses both state and trait anxiety. In the present study, exclusively trait anxiety items were applied, that is items describing the individual's usual feelings. The STAI-T Anxiety Scale assesses trait anxiety by exploring the individual's typical emotional state. Trait anxiety is considered a relatively stable and enduring characteristic of a person's personality, independent of the specific context of evaluation. It represents the inclination or tendency to perceive stimuli and environmental situations as threatening or potentially dangerous. This scale is made up of 20 items.

2.1.3 Beck Depression Inventory II (BDI-II)

The Beck Depression Inventory II (BDI-II) (Beck, 1996) is a self-report questionnaire based on symptoms described in the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) enabling the measurement of depressive severity. The scale consists of 21 items, with four response options presented on a scale from 0 to 3, resulting in a total score ranging from 0 to 63 with higher scores indicating more severe depressive symptoms. The scores related to STAI-T and BDI-II are reported in Table 2.

Table 1 scores related to STAI-T and BDI-II

STAI-T State-Trait Anxiety Inventory			
MIN	MAX	MEAN	SD
14,64	3,08	13,69	2,25
BDI-II Beck Depression Inventory II			
MIN	MAX	MEAN	SD
0	47	14,78	11,37

2.2. Procedure

Each participant completed the entire battery, which comprised tasks and questionnaires evaluating either exteroceptive or interoceptive bodily dimensions.

2.2.1 Exteroceptive Bodily Dimensions

2.2.1.1 Body Image - Photographic Figure Rating Scale (PFRS) - Body Uneasiness Test (BUT)

Body Image refers to the subjective perception, thoughts, and feelings regarding the size, shape, and physical characteristics of their body (Longo, 2016). To assess this dimension, we employed both a behavioural task, the *Photographic Figure Rating Scale (PFRS) task*, and a self-report questionnaire, the *Body Uneasiness Test (BUT)*.

The PFRS, adapted from the study by Naor-Ziv et al. (2020), was used to evaluate participants' perception of body image and their degree of dissatisfaction with their physical appearance. In this task participants were shown a series of ten silhouette images representing a wide range of body sizes, ranging from extremely thin to extremely obese. The task aimed to assess participants' subjective perceptions of their body and their ideal body image, as well as to assess their belief about how others perceive their body. The ten images were calibrated according to Body Mass Index (BMI) values (Swami et al., 2008). Each silhouette corresponded to a specific BMI value, ranging from Image 1 with a BMI of 16 to Image 10 with a BMI of 40. In more details: Image 1 (BMI = 16), Image 2 (BMI = 18), Image 3 (BMI = 21), Image 4 (BMI = 23), Image 5 (BMI = 25), Image 6 (BMI = 28), Image 7 (BMI = 31), Image 8 (BMI = 33), Image 9 (BMI = 36), and Image 10 (BMI = 40). This calibration provided a standardized representation of body sizes in the scale. The images were presented in two separate runs: one in ascending order (from the thinnest to the heaviest) and one in descending order (from the heaviest to the thinnest). The order of presentation was randomized across participants to minimize order effects and response biases. During each presentation, participants selected a single image based on their perceived similarity to their own current physique, their ideal body image, and

their perception of how others see their body. Hence, each participant provided us with two judgments per presentation (one for both ascending and descending order). At the end of the two presentations, each participant had selected two images for each condition. The image was associated with a specific BMI so, we calculated the average BMI from the BMI values of the two selected. Based on the height and weight of each participant, we calculated the real BMI (BMI R). Based on the data collected from the participants' rankings on the PFRS, we calculated the mean BMI for each participant's perceived actual physique (BMI A), ideal body image (BMI I), and perception of how others see their body (BMI O). These means were derived from the participants' rankings of the silhouette images on the PFRS. We also calculated the differences between the participants' real BMI (BMI R) and the mean BMI for each respective category ΔAR , as the difference between BMI A and BMI R, ΔIR , as the difference between BMI I and BMI R, and ΔOR , as the difference between BMI O and BMI R. These differences provided insights into the participants' level of dissatisfaction with their current physique, ideal body image, and how they perceive others' views of their body.

The Body Uneasiness Test is a questionnaire designed to assess individuals' attitudes towards their own body image. Developed by Cuzzolaro et al. (Cuzzolaro M, 1999), the BUT (Cuzzolaro et al., 2006; Cuzzolaro & Fassino, 2018; Marano et al., 2007) consists of 34 items (BUT-A) and a list of 37 body parts (BUT-B), characteristics, or functions. Participants rate each item on a scale ranging from "Never" (0) to "Always" (5), with higher scores indicating a greater level of impairment or uneasiness. The BUT calculates measures of overall severity and distress related to body uneasiness. These include the Global Severity Index (GSI), defined as BUT A score, and Positive Symptom Total (PST) defined as BUT B.

2.2.1.2 Spatial Tactile Acuity - Two-point discrimination task (2PD) task

Spatial Tactile Acuity refers to the ability to precisely perceive the location and quality of touch (Harvie et al., 2018). This dimension was evaluated through the two-point discrimination (2PD) task, which assesses the ability of participants to identify two closely spaced points on a small area of the skin and measures the accuracy of their discrimination skills (Weber, 1996). We compared two body parts chest and thigh used as targets with the neck used as reference (Spitoni et al., 2015). In our study, we utilized pairs of wooden sticks with varying distances between them as tactile stimuli. The participants received tactile stimulation on three different body parts: the chest, thigh, and nape. The nape served as the reference body part, while the chest and thigh were considered the target body parts. We implemented two experimental conditions: one in which participants received a pair of stimuli administered to the nape and a pair on the chest, and in another condition a pair of taps was

given on the nape and thigh. Each pair of stimuli consisted of taps delivered to the designated body parts. The size of the stimuli, or the distance between the contact points, ranged from 4 to 6 cm. The experiment consisted of 30 trials per condition, resulting in a total of trials 60 (20 trials per size). During each trial, the reference stimulus was a fixed distance of 5 cm. On the target body part, the distance between the contact points could vary between 4, 5, or 6 cm⁵. The task assigned to the participants was to indicate which of the two stimuli they perceived as having a greater amplitude. The values reported are the percentages of trials in which participants provided correct responses, underestimated, or overestimated the distance between the two points. From this task, we quantified the following variables: the correct response for the two target body parts, chest (C-che) and thigh (C-thi); the overestimation for both chest (O-che) and thigh (O-thi) calculated by the errors and overestimation of the body parts compared to the reference and similarly, the underestimation for chest (U-che) and thigh (U-thi) calculated by errors and underestimation of the body parts.

2.2.1.3 Body Structural Representation - Finger Localization Task (FLT)

Body Structural Representation (BSR) refers to knowledge about the topological organization of bodies, outlining how different body parts interrelate within a spatial configuration, focusing on the spatial positioning of each body part related to others (Longo, 2016). This dimension was evaluated through the Finger Localization Task (Benton, 1983), which requires participants to identify and differentiate stimulated fingers in three different conditions. Participants were seated in front of a table with their hands placed on the table, palms up, and their fingers extended and slightly separated. The test consisted of three tasks, with ten trials for each hand in each task. In the first task (a), participants were required to identify whether the experimenter touched a finger on their left hand or their right hand. The second task (b) involved participants identifying which finger on their left hand or right hand was touched by the experimenter, with their hands hidden from view. Finally, in the third task (c), participants had to identify pairs of fingers on their left hand or right hand that were touched by the experimenter, while their hands remained hidden from view. Participants indicated their responses by pointing to the correct answer on an outline of a human hand, correct responses were recorded for each trial, and the maximum total score was 60 (Costantini et al., 2020; Fotia et al., 2022). We focused on the third condition, and we calculated the accuracy and included the score of correct responses (HIT) as a variable.

2.2.1.4 Multisensory Integration - Multisensory Integration task (MSI)

Multisensory Integration refers to the process by which inputs from two or more sensory modalities are combined by the nervous system to form a stable and coherent percept of the world (Yau et al., 2015). This dimension was evaluated through the Multisensory Integration (MSI) task aiming at investigating the integration of visual, auditory, and tactile stimuli in participants' perception. The task focused on evaluating their response speed in relation to the presentation of these stimuli (Dumas et al., 2016; Mahoney et al., 2015). Visual stimulation (30 ms of duration) was achieved by incorporating a LED light (5 mm diameter; 200 mcd) placed inside a box. Tactile stimulation was provided using a constant-current electrical stimulator (Digitimer DS7A, Digitimer Ltd., Welwyn Garden City, UK), delivering electrical pulses (duration of 100 μ s), via electrodes attached to the participant's right middle finger. The auditory stimulation was introduced by playing brief auditory beeps. The A stimulus consisted of a pure tone (1000 Hz; 30 ms of duration) presented approximatively at 60 dB using a buzzer. A and V stimuli were delivered through an in-house box containing a fixation cross, the buzzer. All stimuli were administered using the E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA, USA) connected to a TriggerStation™ (BRAINTRENDS LTD 2010, Rome, Italy).

The experiment consisted of a total of 180 trials including one of six different conditions: visual-only (V), tactile-only (T), auditory-only (A), visuo-tactile (VT), audio-visual (AV), and audio-tactile (AT). These conditions were presented in a randomized order, with 30 trials assigned to each condition. Participants were instructed to respond promptly using a foot pedal response pad positioned under their right foot. They were asked to press the pedal as quickly as possible upon perceiving any stimulus presented during the task. For each multisensory pair—audio-visual (av), audio-tactile (at) and visuo-tactile (vt)—the analysis involved calculating the area-under-the-curve (AUC) subtended by the distribution of reaction times to multisensory stimuli as compared to the distribution of reaction times to unimodal stimuli. Hence, we included as a variable AUC-av, AUC-at and AUC-vt that represent a proxy of the magnitude of multisensory integration for audio-visual, audio-tactile and visuo-tactile stimuli, respectively.

2.2.1.5 Multisensory Temporal Resolution - Simultaneity Judgment task (SJ)

Multisensory Temporal Resolution refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. This principle highlights the critical role of temporal proximity in influencing the nervous system's integration of diverse sensory information (Sarko et al., 2012).

This dimension was evaluated through the Simultaneity Judgment (SJ) task, which aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Auditory stimuli were delivered through headphones and consisted of a 3,500-Hz pure tone lasting 30ms. Tactile stimuli were administered using two constant-current electrical stimulators (Digitimer DS7A), which controlled two pairs of neurological electrodes attached to the participant's right and left middle fingers. Tactile stimuli were single, constant voltage, rectangular monophasic pulses lasting 100 μ s (Di Cosmo, Costantini, Ambrosini, et al., 2021; Ferri et al., 2017).

During the task, participants were blindfolded and comfortably seated at a table, with their index fingers resting on separate keys of a response box. The intensity of the stimuli was adjusted to each participant's detection threshold, set at 100% for both auditory and tactile stimuli. In each trial, two stimuli were presented in opposite hemispaces, with stimulus pairs randomly interleaved at various stimulus onset asynchronies (SOAs): ± 450 , ± 350 , ± 200 , ± 120 , ± 70 , ± 40 , ± 15 , and 0 ms.

Participants had to indicate whether the two stimuli were presented simultaneously or not using the response box. The AT-SJ task comprised two blocks, each consisting of 120 trials, resulting in a total of 240 trials (16 trials per SOA). The association between the side of presentation (right or left) and the modality (auditory or tactile) was balanced across trials, and the stimulus-response association was counterbalanced between blocks. We included from this task two parameters: the point of subjective equality (PSE-sj), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the 'just noticeable difference' (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli.

2.2.1.6 Peripersonal Space - Peripersonal Space task

Peripersonal Space refers to the space surrounding the body where the integration of stimuli on the body and from the external environment is facilitated (Rabellino et al., 2020).

This dimension was evaluated through the Peripersonal Space (PPS) task (Canzoneri et al., 2012; Di Cosmo, Costantini, Spadone, et al., 2021; Di Cosmo et al., 2018), which allows evaluating the individual's boundaries of the peripersonal space by assessing the optimal temporal interval for the integration of tactile and auditory stimuli (Ferri et al., 2015; Spadone et al., 2021). During the experiment, the participants were blindfolded and seated comfortably at a table with their right hand resting on the palm. The equipment used consisted of headphones and a constant-current electrical stimulator (Digitimer DS7A) that controlled a pair of electrodes attached to the participant's right middle finger. Each experimental trial involved the presentation of a looming sound along with a

tactile stimulus. The tactile stimulus was delivered at five different time delays from the onset of the auditory stimulus (D1: 300 ms, D2: 800 ms, D3: 1500 ms, D4: 2200 ms, and D5: 2700 ms). Tactile stimulation could also be delivered during the silent periods preceding the presentation of the sound (D0: -700 ms). The remaining trials were catch trials, involving only auditory stimulation. The experiment consisted of a total of 80 trials, including 50 post-trials (10 for each delay), 10 pre-trials, and 20 catch trials. The participants were instructed to respond as quickly as possible to the tactile stimulus by pressing a button on a response box with their left index finger. They were required to ignore the auditory stimulus. After each trial, there was an intertrial interval of 1000 ms to allow for rest and preparation for the next trial (Ardizzi & Ferri, 2018; Canzoneri et al., 2012; Di Cosmo, Costantini, Spadone, et al., 2021). We included as a variable the point of subjective equality (PSE-pps) of the psychometric function that is taken as a proxy of the peripersonal space boundary.

2.2.1.7 Temporal Tactile Acuity - Temporal Order Judgment (TOJ, uncrossed hands)

Temporal Tactile Acuity refers to the ability to perceive and discriminate temporal aspects of tactile stimuli. It involves the capacity to detect and distinguish temporal characteristics of sensations related to touch (Laasonen et al., 2001). This dimension was evaluated through the Temporal Order Judgment. In a typical Temporal-Order Judgment (TOJ) task, participants are tasked with determining the order of two tactile stimuli presented sequentially to their left and right hands. When the hands are in an “uncrossed” position (toju), participants can rely on tactile and proprioceptive cues related to their body posture, utilizing a body-centred reference frame (Heed et al., 2014). In the Temporal-Order Judgment task, participants were seated at a table with their hands placed palm down on the table surface. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli, (i.e., stimulus onset asynchrony SOA), was randomly assigned from 22 intervals. In the uncrossed condition, it ranged from -450 to 450 ms (± 450 , ± 300 , ± 200 , ± 150 , ± 100 , ± 75 , ± 50 , ± 40 , ± 30 , ± 15 , ± 5 ms). Negative and positive intervals indicated whether the left or right hand was stimulated first. The inter-trial intervals varied between 2000 and 4000 ms. Each condition comprised 176 trials, with 8 trials per SOA¹⁹. Tactile stimuli were delivered using two constant-current electrical stimulators (Digitimer DS7A), which controlled pairs of neurological electrodes attached to the dorsal surface of the middle fingers. The stimuli were supra-threshold vibrotactile stimuli oscillating at 100 Hz, with a total duration of 30ms. During the experiment, participants were blindfolded, and white noise was presented through headphones to mask any auditory cues. Thus, participants could only perceive the tactile stimulation applied to their fingers. Participants rested their right and left index fingers on two response buttons located on the table. They were instructed to make two-alternative forced-choice judgments regarding the order of stimulation by pressing the button under the index finger of the hand they believed was stimulated

earlier or later than the other. The two response strategies (earlier and later) were counterbalanced. Trials with response times exceeding 3000 ms or without a response were re-presented at the end of the corresponding block, ensuring an equal number of trials across all experimental conditions. No feedback was provided to the participants. From this task, we included as a variable the just noticeable difference (JND-toju), as a measure of precision, and the proportion of correct responses that represents the smallest interval at which the participants can reliably decide which sensory input of the two presented was first.

2.2.1.8 Sensorimotor functions - Temporal Order Judgment (TOJ, crossed hands) - Laterality Judgement Task (LJT)

To perceive the location of touch in space, the brain combines information about touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands (Azañón et al., 2016). This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (toj)(Ferri et al., 2016).

In crossed conditions, participants were instructed to cross their arms over their wrists. The two possible arm positions (right over left and vice versa) were counterbalanced across participants, and the order was randomly assigned to each participant. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli ranged from -900 to 900 ms (± 900 , ± 600 , ± 400 , ± 300 , ± 200 , ± 150 , ± 100 , ± 80 , ± 60 , ± 30 , ± 10 ms). The mean response times (RT) and participant responses were calculated by considering the temporal distance between stimuli (SOA). From this task, we included as a variable the just noticeable difference (JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first; and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions. SC-toj is a global indicator of differences, which provides an overarching measure of the divergence between the two conditions and assess increases in judgment reversals resulting from the arm-crossing manipulation.

The Laterality Judgement Task is designed to assess participants' ability to judge the lateral orientation of presented hand images (Mibu et al., 2020). In this task, grey-scale pictures depicting the dorsal view of both right and left hands are presented individually on a computer screen. The hand images are displayed in six different clockwise orientations: upright 0°, 60°, 120°, 180°, 240°, and 300°, with

the upright orientation representing the hand with the fingers pointing upwards. All participants were right-handed, as assessed by self-report.

Participants were seated in front of a computer screen at approximately 40 cm. Each trial commences with the presentation of a central fixation cross, which remains on the screen for 500 milliseconds to ensure participants' attention is focused. Following the fixation cross, a hand image is presented at the centre of the screen. The hand images can represent either a left or a right hand. During the task, participants were instructed to judge the laterality (left or right) of the observed hand image as accurately and quickly as possible. They have a maximum response time window of 4000 milliseconds to provide their judgment. Participants use their left and right index fingers to press designated response keys that correspond to their judgment of the hand's laterality. The left key is pressed for a judgment of "left hand," while the right key is pressed for a judgment of "right hand" (Ferri et al., 2011). The LJT comprises a total of 144 trials, with each orientation condition being presented 12 times. The task aims to assess participants' ability to mentally rotate the presented hand images and accurately determine their laterality. We calculated slopes, which reflect the efficiency of the neural mechanism underlying the mental rotation process: a smaller slope indicates higher neural efficiency in mental rotation. We quantified slopes for both hands, indicated as Mental Rotation Efficiency for the left hand (MRE-lh) and the right hand (MRE-rh), illustrating the efficiency of the respective mental rotation processes.

2.2.2 Interoceptive Bodily Dimensions

2.2.2.1 Interoceptive Accuracy - Heartbeat Detection task - Heartbeat Counting task.

The tapping task, also known as the Heartbeat Detection or tracking task (Brenner & Ring, 2016; McFarland RA., 1975), is used to assess participants' ability to accurately perceive and count their own heartbeats. During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. The task consisted of two time periods, each lasting 2 minutes, with a pause between them. Following each time interval, participants were required to verbally report their level of confidence in their perceived accuracy of heartbeat detection. This confidence rating was recorded using a scale from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

The Heartbeat Counting task, is used to assess participants' ability to accurately perceive and count their own heartbeats. This task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals.

During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and count the number of heartbeats they feel. The task consists of four different time periods: 25 seconds, 30 seconds, 45 seconds, and 100 seconds³⁴. These time periods are presented in a random order to avoid predictable patterns. During each time interval, participants were instructed to focus their attention on their heart activity and bodily sensations. They were specifically asked to count and keep track of their felt heartbeats without engaging in any physical manipulations, such as taking their pulse or using external cues. Participants were also discouraged from using the duration of the time interval as a basis for estimating the number of heartbeats. The task begins with a 10-second introductory phase to allow participants to settle into the task. Each period is presented separately, with a pause between each trial. Participants are instructed to count only the heartbeats that they feel internally, excluding any perceived or anticipated beats, i.e., those they might infer, or estimate based on external strategies such as taking their pulse, using other physical manipulations, or estimating based on the duration of the time interval. Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. These responses were manually recorded by the experimenter for later analysis. We calculated the accuracy for both Heartbeat Detection task (Acc-d) and Heartbeat Counting task (Acc-c).

2.2.2.2 Interoceptive Sensibility - Heartbeat Detection task - Heartbeat Counting task confidence level - Body Perception Questionnaire (BPQ) - Multidimensional Assessment of Interoceptive Awareness (MAIA)

We evaluated this dimension through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d) and the Heartbeat Counting task (Con-c). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat). We also used two self-report questionnaires: the Body Perception Questionnaire (BPQ)(Poli, Giovanni, et al., 2021; Porges, 1993) and the Multidimensional Assessment of Interoceptive Awareness (MAIA) (Mehling et al., 2012). The Body Perception Questionnaire (BPQ)(Poli, Maremmanni, et al., 2021; Porges, 1993) is a self-report measure designed to assess body awareness and autonomic symptoms. It consists of 22 items and a three-factor structure including a body awareness factor, a supradiaphragmatic factor, and a subdiaphragmatic/body awareness factor.

The body awareness (BOA) factor consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) involved in regulating of the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), includes items related to subdiaphragmatic issues. The MAIA (Mehling et al., 2012) is composed of 32 items on a 6-points Likert scale, in which the participant must rate “how often each statement applies to you generally in daily life,” with ordinal responses coded from 0 (“never”) to 5 (“always”). This multidimensional instrument measures Interoceptive sensibility on eight scales: (1) Noticing, the awareness of one's body sensations; (2) Not-distracting, the tendency not to ignore or distract oneself from sensations of pain or discomfort; (3) Not-worrying, the tendency not to experience emotional distress or worry with sensations of pain or discomfort; (4) Attention regulation, the ability to sustain and control attention to body sensation; (5) Emotional awareness, the awareness of the connection between body sensations and emotional states; (6) Self-regulation, the ability to regulate psychological distress by attention to body sensations; (7) Body listening, the tendency to actively listen to the body for insight; and (8) Trusting: the experience of one's body as safe and trustworthy.

2.2.2.3. Interoceptive Awareness - Heartbeat Detection task - Heartbeat Counting task

Interoceptive Awareness is the metacognitive awareness of interoceptive accuracy and refers to the correspondence between objective interoceptive accuracy and subjective confidence report (Garfinkel et al., 2015; Suzuki et al., 2013). So, we quantified the participant's awareness by comparing the accuracy and the sensibility in both the Heartbeat Detection task (Aw-d) and the Heartbeat Counting task (Aw-c).

2.3. Statistical Analysis: Machine Learning Approach

Partial Least Squares Regression (PLSR) was employed to examine the contributions of interoceptive and exteroceptive bodily dimensions to anxiety and depression symptoms. PLSR is particularly suitable for addressing multicollinearity among predictors and handling high-dimensional datasets.

In this study, we applied Partial Least Squares Regression (PLSR), a linear regression technique designed to reduce the dimensionality of the feature space. PLSR is particularly effective in mitigating overfitting, especially when dealing with highly correlated predictors. The key aspect behind PLSR is that the observed data are influenced by a limited number of latent variables that are not directly observable or measurable. By constructing regression models on these latent components, PLSR identifies the most relevant information within the independent variables, while simultaneously reducing the complexity of the regression problem by employing a smaller number of components

than the original count of independent variables. PLSR is a supervised learning approach that selects components that maximize the covariance between independent and dependent variables, making it another form of supervised learning algorithm. The PLSR algorithm requires an a priori selection of one parameter, known as a hyperparameter, namely the number of uncorrelated components (K) to be used in the regression. To optimize K, it is essential to partition the dataset into a training set, validation set, and test set. The training set is used to estimate PLSR weights, the validation set is used to determine the optimal K, and the test set is used to assess the model's generalization performance. However, this division reduces the available sample size, posing a trade-off between optimization and model reliability. To minimize sample loss and ensure model generalization, we employed cross-validation (CV). In this approach, the dataset is divided into multiple folds, and the model is iteratively trained on all but one-fold, which is used for out-of-sample evaluation. The leave-one-out cross-validation (LOO-CV) strategy, where the number of folds equals the number of samples, was implemented to provide a rigorous estimate of model generalizability. However, when hyperparameter tuning is required, a simple cross-validation approach may not be sufficient. In such cases, a nested cross-validation (nCV) procedure is preferred. Nested cross-validation consists of two loops: an outer loop (to evaluate the model's generalization performance) and an inner loop (to determine the optimal hyperparameter values). Specifically, in each iteration:

In this study, a leave-one-out nCV was used to evaluate the PLSR model performance and the optimal number of components. Two separate models were constructed, each using a different dependent variable: Anxiety (STAI-T) and Depression (BDI-II).

For each of them, PLSR was used to test three models, each of which used exteroceptive, interoceptive, and intero-exteroceptive variables (BMI (R), A (actual), I (ideal), O (other), Δ AR, Δ IR, Δ OR, Pt. tot. A, Pt. tot. B, C-che, O-che, U-che, U-thi, O-thi, C-thi, HIT, AUC-av, AUC-at, AUC-vt, PSE-sj, JND-sj, PSE-pps, JND-toju, JND-tojc, SC-toj MRE-lh, MRE-rh, Acc-d, Acc-c, Con-d, Con-c, BOA, SUP, BOA/SUB, 1M-8M, Aw-d, Aw-c) as independent variables, resulting in a total of six models. Each model was trained and tested separately.

The regression performances of the models were evaluated through correlation analyses between the predicted values and the actual values (which likely stand for some specific variable or outcome). The correlation coefficient, denoted as "r," is reported for each tested model. The degrees of freedom (DF) and the significance of the null hypothesis (p) are also reported in the analysis. These values help assess the strength and significance of the correlations between the predicted and actual values.

Furthermore, the statistical significance of the weights was assessed using a randomization procedure, which involved constructing a confidence interval for the null hypothesis of each weight being zero (iterating the same algorithm 10^6 times on random shuffled outcomes).

The rationale for developing two distinct models was to identify both shared and specific bodily predictors for anxiety and depression. By examining these dimensions separately first and then combined, we aimed to compare the underlying bodily processing mechanisms, determining whether specific aspects uniquely contribute to each condition or if common patterns emerge across both.

3. Results

3.1 Contribution of exteroceptive bodily dimension to anxiety and depression

The model testing the predictive impact of exteroceptive bodily dimensions to anxiety was significant after cross-validation (see figure 1a.). A significant positive correlation between the actual anxiety score and the predicted anxiety score was obtained ($r = 0.60891$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A, A (actual), spatial tactile acuity (C-che, C-thi, U-che), body structural representation (HIT), multisensory integration (AUC-at), multisensory temporal resolution (JND-sj), temporal tactile acuity (JND-toju) and sensorimotor functions (SC-toj).

The model testing the predictive impact of exteroceptive bodily dimensions to depression was significant after cross-validation (see figure 1b.). A significant positive correlation between the actual depression score and the predicted depression score was obtained ($r = 0.61935$, $p < 0.001$). Dimensions that significantly contributed was body image (BUT A, O (other), ΔAR , ΔOR).

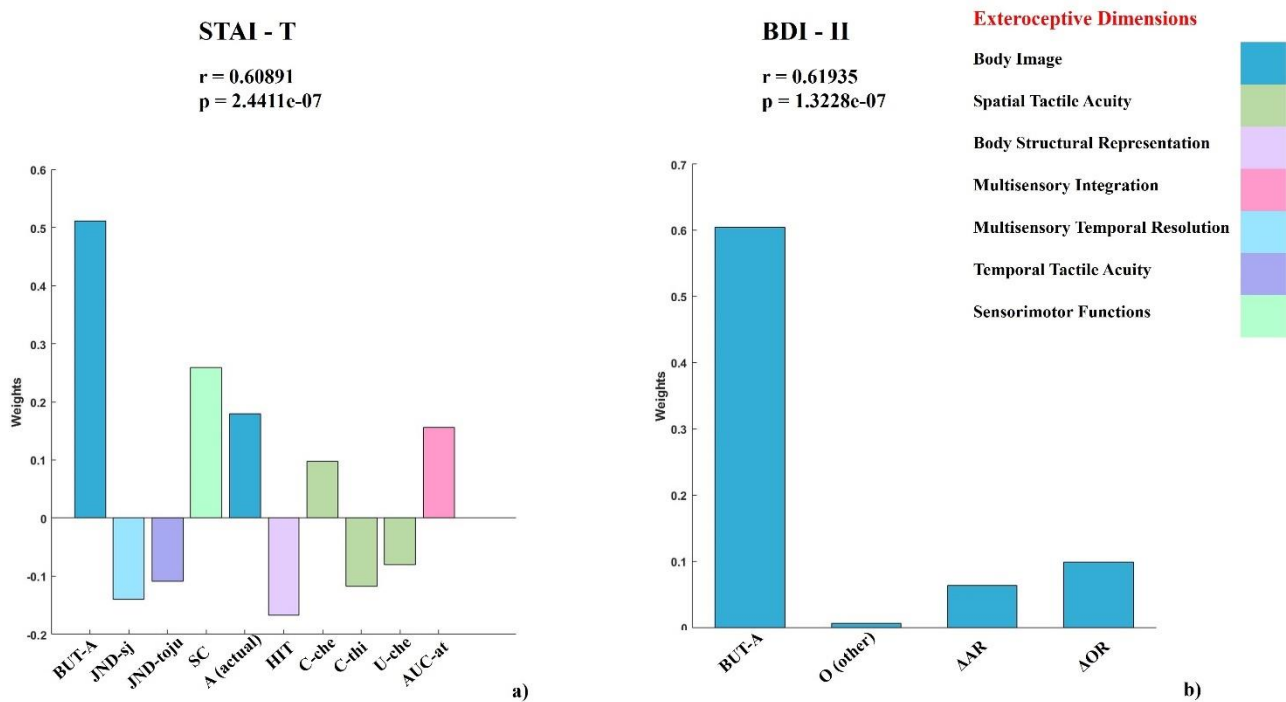


Figure 1. Contribution of exteroceptive bodily dimensions to anxiety and depression. PLSR out-of-sample prediction of STAI – T and BDI-II traits shows significant correlations between true and predicted values (R and p values reported). a) STAI-T: Regression weights for exteroceptive variables (BUT A, JND-sj, JND-toju, SC-toj, A (actual), HIT, C-che, C-thi, U-che, AUC-at). b) BDI-II: Weights for variables (BUT A, O (other), Δ AR, Δ OR). Only weights exceeding the 95% confidence interval of the null hypothesis are reported.

3.2 Contribution of interoceptive bodily dimension to anxiety and depression

The model testing the predictive impact of interoceptive bodily dimensions to anxiety was significant after cross-validation (see figure 2a). A significant positive correlation between the actual anxiety score and the predicted anxiety score was obtained ($r = 0.69199$, $p < 0.001$). Dimensions that significantly contributed were interoceptive accuracy (Acc-c) and interoceptive sensibility (2M, 3M, 7M, 8M, BPQ-SUP, BPQ-BOA/SUB).

The model testing the predictive impact of interoceptive bodily dimensions to depression was significant after cross-validation (see figure 2b). A significant positive correlation between the actual depression score and the predicted depression score was obtained ($r = 0.67613$, $p < 0.001$). Dimensions that significantly contributed were interoceptive accuracy (Acc-c) and interoceptive sensibility (3M, 4M, 6M, 8M, BPQ-SUP, BPQ-BOA/SUB).

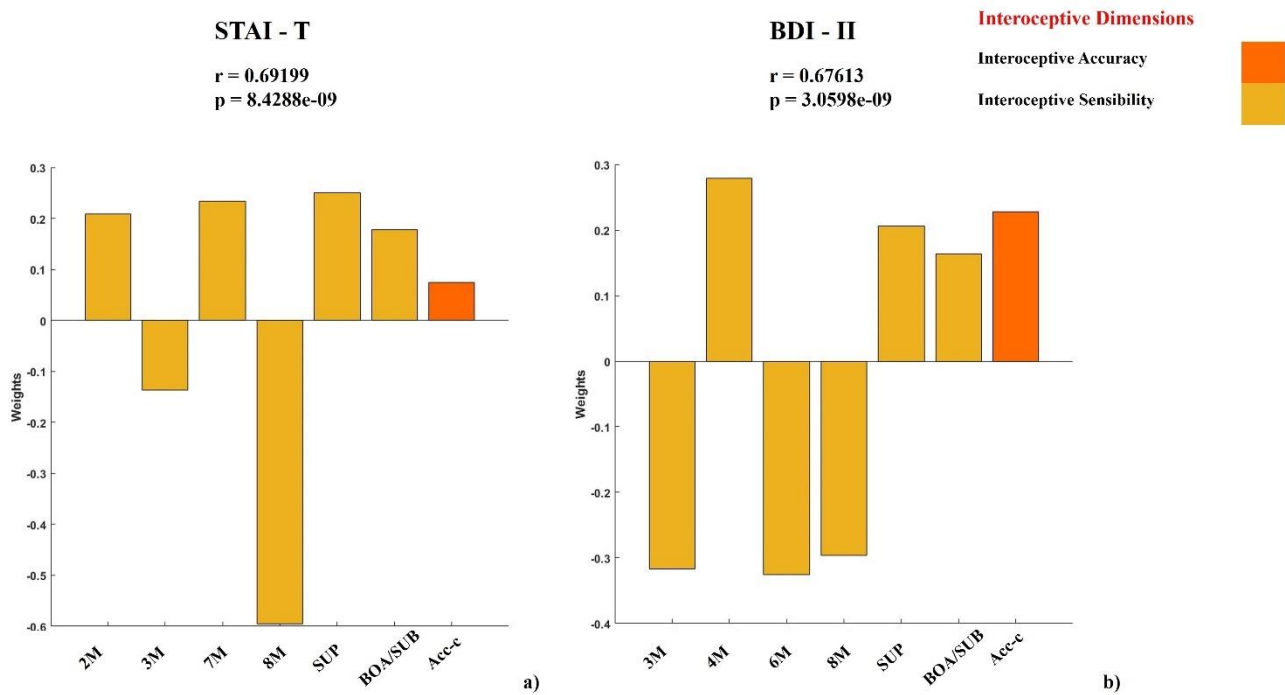


Figure 2. Contribution of interoceptive bodily dimensions to anxiety and depression. PLSR out-of-sample prediction of STAI – T and BDI-II traits shows significant correlations between true and predicted values (R and p values reported). a) STAI-T: Regression weights for interoceptive variables (2M, 3M, 7M, 8M, BPQ-SUP, BPQ-BOA/SUB, Acc-c). b) BDI-II: Regression weights for interoceptive variables (3M, 4M, 6M, 8M, BPQ-SUP, BPQ-BOA/SUB, Acc-c). Only weights exceeding the 95% confidence interval of the null hypothesis are reported.

3.3 Contribution of both exteroceptive and interoceptive bodily dimensions to anxiety and depression

The model testing the predictive impact of both exteroceptive and interoceptive bodily dimensions to anxiety was significant after cross-validation (see figure 3a). A significant positive correlation between the actual anxiety score and the predicted anxiety score was obtained ($r = 0.71091$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), body structural representation (HIT), sensorimotor function (SC-toj) and interoceptive sensibility (2M, 8M, BPQ-SUP).

The model testing the predictive impact of both exteroceptive and interoceptive bodily dimensions to depression was significant after cross-validation (see figure 3b). A significant positive correlation between the actual depression score and the predicted depression score was obtained ($r = 0.5715$,

$p < 0.001$). Dimensions that significantly contributed were body image (BUT-A) and interoceptive sensibility (6M, 8M, BPQ-SUP).

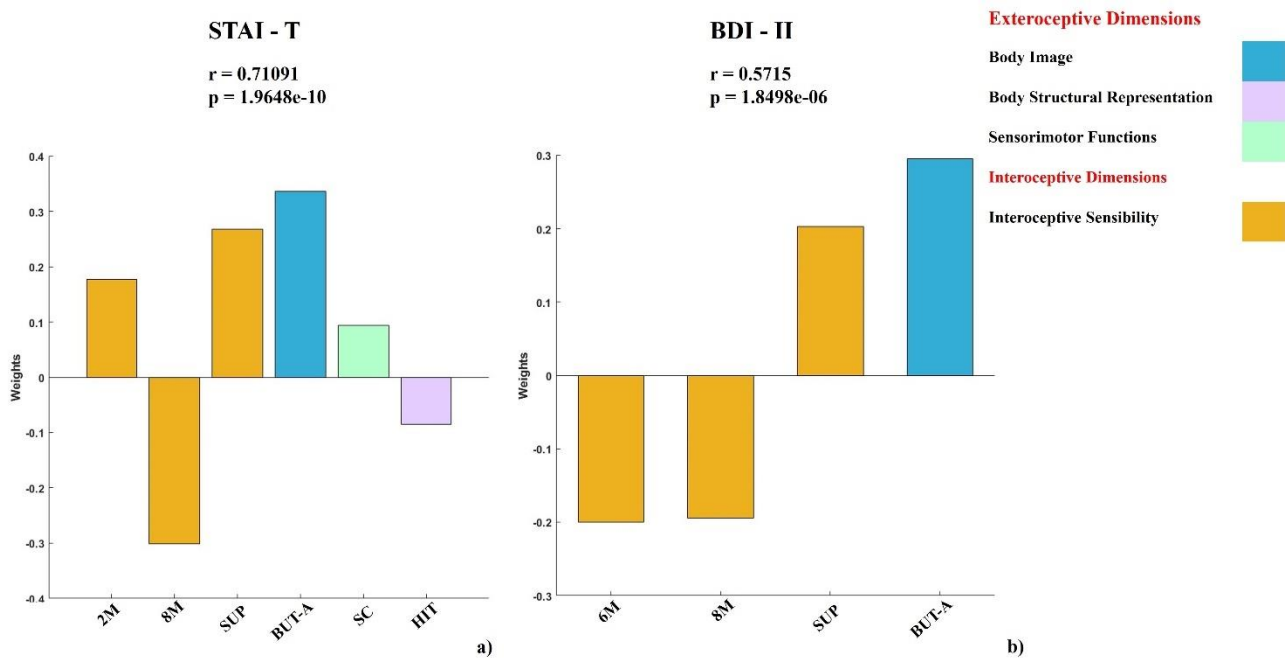


Figure 3. Contribution of both exteroceptive and interoceptive bodily dimensions to anxiety and depression. PLSR out-of-sample prediction of STAI – T and BDI-II traits shows significant correlations between true and predicted values (R and p values reported). a) STAI-T: Regression weights for exteroceptive and interoceptive variables (BUT A, HIT, SC-toj, 2M, 8M, BPQ-SUP). b) BDI-II: Weights for variables (BUT A, 6M, 8M BPQ-SUP). Only weights exceeding the 95% confidence interval of the null hypothesis are reported.

4. Discussion

The present study investigated the contribution of exteroceptive and interoceptive bodily dimensions to anxiety and depression. For both anxiety and depression, we determined the contribution of exteroceptive and interoceptive bodily dimensions separately and in combination to explore the overlapping and distinct contribution. To this aim we employed a comprehensive battery of behavioural tasks and self-report questionnaires to assessed exteroceptive and interoceptive bodily dimensions and then, we used Partial Least Squares Regression (PLSR) to test the predictive power of these dimensions and to identify the specific and common contribution of each bodily dimension. A summary of the significant predictors for each model is reported in Table 1.

Table 1 Contributions of exteroceptive and interoceptive dimensions to anxiety and depression.

	STAI - T	BDI - II
Exteroception	Body image Spatial tactile acuity Body structural representation Multisensory integration Multisensory temporal resolution Temporal tactile acuity Sensorimotor functions	Body image
Interoception	Interoceptive accuracy Interoceptive sensibility	Interoceptive accuracy Interoceptive sensibility
Exteroception and Interoception	Body image Body structural representation Sensorimotor functions Interoceptive sensibility	Body image Interoceptive sensibility

4.1 Contribution of exteroceptive bodily dimensions to anxiety and depression

Our results indicate that exteroceptive bodily dimensions significantly predict both anxiety and depression, but they contribute in distinctly different ways across the anxiety and depression. In anxiety, relevant predictors included body image (BUT-A, A (actual)), spatial tactile acuity (C-che, C-thi, U-che), body structural representation (HIT), multisensory integration (AUC-at), multisensory temporal resolution (JND-sj), temporal tactile acuity (JND-toju) and sensorimotor functions (SC-toj). In contrast, the predictive pattern for depression included only body image (BUT A, O (other), Δ AR, Δ OR). Body image emerged as a strong common predictor for both anxiety and depression, aligning with prior literature highlighting that body image disturbances and body image dissatisfaction play a central role in both conditions (e.g. Barnes et al., 2020; DeBraganza & Hausenblas, 2010; Paans et al., 2018b). In the anxiety model, the relevant predictors were BUT-A (global uneasiness) and A (actual), a subjective estimation of one's own body size. Body image alterations in anxiety may reflect heightened vigilance toward physical appearance and social evaluation, especially in conditions characterized by fear of negative judgment. This pattern may indicate self-focused monitoring and

sensitivity to perceived bodily imperfections or deviations from an internal ideal (Dou et al., 2023; Vannucci & Ohannessian, 2017). In contrast, in the depression model the relevant predictors were BUT-A, O (others' perception), Δ AR (difference between actual and real body size), and Δ OR (difference between others' perception and real body size). This suggests that in depression, body image disturbances are more related to dissonance between self-perception, perceived social views, and objective body measure. The involvement of discrepancy variables may reflect broader cognitive-affective distortions, where the body is perceived as negative (Pylvänäinen et al., 2021). The inclusion of others' perception may also point to internalized social judgments, which are often amplified in depression and contribute to a pervasive sense of inadequacy or shame.

Hence, despite its predictive value in both conditions, body image likely reflects qualitatively distinct underlying processes in anxiety and depression, anticipatory and more related to worry about appearance in the former, more linked to negative self-view and feelings of inadequacy in the latter.

In addition to body image, anxiety was significantly predicted by other exteroceptive dimensions. These findings suggest that anxiety may be associated with more disruptions in the processing of bodily signals from the external environment than depression. This pattern is consistent with theoretical models positing heightened sensory vigilance and hyper-responsiveness to threat in anxiety, which may amplify sensitivity to external bodily cues and contribute to altered perception of space and time (Vagnoni et al., 2012, 2015).

Interestingly, in contrast to previous findings linking trait anxiety with an expanded peripersonal space (Iachini et al., 2015; Sambo & Iannetti, 2013), peripersonal space did not significantly contribute to anxiety in our sample. One possible explanation may be linked to methodological differences: previous studies (Iachini et al., 2015; Ruggiero et al., 2017; Sambo & Iannetti, 2013) typically assessed PPS under emotionally salient or threat-related conditions, such as the presentation of looming or aversive stimuli. In contrast, our task measured PPS boundaries in a neutral, non-affective context.

4.2 Contribution of interoceptive bodily dimensions to anxiety and depression

Our findings indicate that interoceptive accuracy and sensibility significantly predict both anxiety and depression with substantial overlap in the contributing predictors. Shared predictors included interoceptive accuracy (Acc-c) and interoceptive sensibility (3M not worrying, 8M trusting, BPQ-SUP supradiaphragmatic reactivity and BPQ-BOA/SUB subdiaphragmatic/body awareness). Anxiety-specific predictors included 2M not-distracting and 7M body listening, while depression-

specific predictors included 4M attention regulation and 6M self-regulation. These results are consistent with the previous studies suggesting that both anxiety and depression often involve disruptions in how internal bodily signals are perceived and interpreted (Paulus & Stein, 2010; Quadt et al., 2018).

In anxiety, the contribution of interoceptive accuracy is consistent with prior studies reporting increased accuracy in heartbeat detection in individuals with high anxiety or panic symptoms (Dunn et al., 2010; Pollatos et al., 2007). This heightened interoceptive accuracy has been interpreted as a manifestation of interoceptive hypervigilance, where internal signals, especially those linked to arousal, are monitored more closely and often interpreted as signs of threat. Specifically, an internal body signal, such as a heartbeat may be associated with negative valence and linked to belief-based negative processes, e.g., “there is something wrong with my heart”, which results in increased worry and potential withdrawal or avoidance behaviours (Paulus & Stein, 2010). This interpretation is also in line with the significant contribution of several aspects of interoceptive sensibility, particularly the contribution of the subscales: not-worrying (2M), attention regulation (3M), body listening (M7), and trusting (M8), suggests that anxiety may be associated not only with heightened interoceptive accuracy, but also with a maladaptive cognitive-affective stance toward beliefs about bodily states, marked by difficulty regulating concern and trust in internal signals (Solano López & Moore, 2019). Moreover, the significant contribution from BPQ-SUP supradiaphragmatic reactivity and BPQ-BOA/SUB subdiaphragmatic/body awareness may reflect a pattern of bodily hypervigilance and excessive internal monitoring. These scales capture a heightened awareness of autonomic and visceral sensations, which may contribute to a state of sustained attention to internal cues, amplifying anxious arousal.

In depression, interoceptive predictors largely overlapped with those found in anxiety. Significant contributors included interoceptive accuracy (Acc-c). This result is consistent with previous findings suggesting that depression is associated with altered interoceptive processing, although in a different form than anxiety. While anxiety appears linked to hypervigilance and heightened awareness of internal signals, depression has often been associated with reduced interoceptive accuracy and blunted emotional resonance with internal states (Dunn et al., 2007; Pollatos et al., 2009). This attenuation may contribute to experiences of emotional numbness and reduced self-awareness, common in depressive states (Quadt et al., 2018; Wiens et al., 2000).

Moreover, the involvement of sensibility aspects such as attention regulation (4M) and self-regulation (6M) suggests that depression may be characterized by difficulties in managing the emotional consequences of internal bodily sensations, even when these are detected accurately. The reduced

capacity to “trust” bodily signals (8M) or to regulate attention toward them may further contribute to a sense of disconnection or unreliability of internal experience (Quadt et al., 2018; Solano López & Moore, 2019). Finally, the contribution of BPQ-SUP supradiaphragmatic reactivity and BPQ-BOA/SUB subdiaphragmatic/body awareness may support the idea that altered interoceptive processing may represent a shared vulnerability across affective disorders. At the same time, the specific contribution of self-regulatory dimensions in depression, such as attention and emotional regulation (4M and 6M), suggests that the two conditions may differ in how bodily signals are interpreted and used. While anxiety appears to be characterized by heightened vigilance and sensitivity to internal cues, depression may involve a diminished ability to regulate emotional functioning.

4.3 Contribution of exteroceptive and interoceptive bodily dimensions to anxiety and depression

When considering interoceptive and exteroceptive predictors together, our results revealed a distinct pattern for anxiety and depression, with only a subset of variables maintaining their significance. These dimensions may represent the most robust and specific bodily aspects for anxiety and depression, considering the interaction between all exteroceptive and interoceptive variables included in the model.

For anxiety, significant predictors included body image (BUT-A), sensorimotor functions (SC-toj), body structural representation (HIT), and interoceptive sensibility (2M not-distracting, 8M trusting and BPQ-SUP supradiaphragmatic reactivity). The contribution of SC-toj, that indicates the sum of differences in the response functions between crossed and uncrossed hand conditions, may reflect a reduced capacity to resolve conflicts between tactile stimuli and spatial location, suggesting difficulty in remapping external sensory inputs (e.g. the information about touched skin location with information about the location of that body part in space). This is consistent with the idea that anxiety is associated with heightened salience of external stimuli due to hypervigilance and elevated sensitivity to external environment. Similarly, the contribution of HIT, a task requiring the localization of touch across fingers, may reflect heightened awareness of external tactile signals and altered structural body representations, further supporting the hypothesis of hypervigilance to external input. The interoceptive predictors that remained significant for anxiety (2M not-distracting, 8M trusting and BPQ-SUP supradiaphragmatic reactivity) further support the idea that anxiety involves maladaptive attentional and evaluative patterns toward bodily signals. The specific contribution of 2M not-distracting may reflect the reduced capacity to disengage from bodily sensations, a feature often

associated with anxious behaviour. Similarly, the contribution of BPQ-SUP supradiaphragmatic reactivity suggests heightened awareness of autonomic sensations which may fuel hypervigilance and distress, as well as a reduced sense of trust in the body (8M). While interoceptive attention can be adaptive in regulating emotional states and anxiety, excessive focus on the same bodily signals may be maladaptive and intensify anxiety (Trevisan et al., 2021). This relationship may be circular, such that increased anxiety also amplifies the interoceptive signals. Together, these findings suggest that anxiety involve an increased sensitivity to external stimuli and a maladaptive focus on internal bodily states.

Significant predictors for depression included body image (BUT-A) and interoceptive sensibility (6M self-regulation, 8M trusting and BPQ-SUP supradiaphragmatic reactivity). This pattern reinforces the centrality of body-related discomfort and altered interoceptive engagement in depressive states. The contribution of BUT-A, consistent across models, confirms that bodily uneasiness is fundamental feature of depression. 6M self-regulation as a specific predictor of depression, highlight difficulties in using interoceptive signals to regulate emotional distress (Li et al., 2024). This finding aligns with theories suggesting that depression involves a weakened connection between bodily sensations and affective responses (Fuchs & Schlimme, 2009; Orphanidou et al., 2023). The contribution of 8M trusting may have a role to the sense of disconnection or unreliability of internal experience (Quadt et al., 2018; Solano López & Moore, 2019). BPQ-SUP supradiaphragmatic reactivity may indicate a disorganized or emotionally unintegrated awareness of internal signals. This may contribute to the experience of bodily fragmentation, numbness, or unreliability often reported in depressive states.

While both 8M trusting and BPQ-SUP supradiaphragmatic reactivity were also predictive of anxiety, their interpretation is different in the two conditions. In anxiety, these dimensions may reflect hypervigilant monitoring and excess of attention in bodily signals; in depression, they may instead indicate a disconnection of the embodied emotional coherence, contributing to a diminished sense of bodily presence.

In conclusion, our findings highlight both shared and distinct bodily dimension that contribute to anxiety and depression. While both conditions involve the contribution from interoceptive accuracy and sensibility, anxiety is characterized by a high exteroceptive predictors that reflect hypervigilant monitoring, whereas depression is predicted by body image, particularly body uneasiness and difficulties in using internal signals for emotional regulation. These results offer novel insights into the embodied features of affective symptoms and support the need for further exploration of these bodily dimensions in clinical population.

CHAPTER 4.

Bodily predictors of daily functioning in older adults: the interactive role of interoception and exteroception dimensions

1. Introduction

Active aging is a process of becoming aware of one's own resources, which is essential to optimize opportunities for health, social participation, and high quality of life as people age (Stenner et al., 2011). A crucial aspect in this process is bodily awareness, as it plays a fundamental role in adapting to age-related changes (Kuehn et al., 2018; Raimo et al., 2021). However, as individuals grow older, they often face increasing difficulties in performing basic everyday tasks and more complex activities, which can significantly impact their independence and well-being. These difficulties arise from the progressive loss of integrity of at least two intertwined dimensions: the interoceptive dimension (Ulus & Aisenberg-Shafran, 2022), which governs daily functional actions (Schmitt & Schoen, 2022) or bodily processes, and the capacity to interact effectively with the external environments. Research shows that aging brings progressive changes in bodily functions, leading to cognitive decline (Murman, 2015) and reduction in daily life functioning (Kuehn et al., 2018). These physiological and neurological changes are closely linked to a deterioration in interoceptive abilities, such as the accuracy and sensibility of perceiving internal bodily signals (Khalsa et al., 2009). As a result, older adults may experience difficulties in tasks requiring bodily awareness, emotional regulation, and interaction with their environment (Charles & Carstensen, 2010; Sardella et al., 2023). These difficulties often manifest as a decline in functional body capacity - an important indicator of health. When functional body capacity is reduced, it not only compromises the quality of life but also has social consequences leading to a greater reliance on medical care and support services (Guralnik et al., 1996).

Hence, interoception represents a central aspect for better understanding the mechanisms underlying active aging, particularly in relation to physical functioning, well-being and daily functioning. Interoception refers essentially to sensations stemming from inside the body such as heartbeats, breaths, temperature, hunger, and thirst (A. D. Craig, 2009; Critchley et al., 2004; Mayer et al., 2006). Interoception can be divided into three distinct components (Garfinkel et al., 2015): interoceptive accuracy, which refers to the objective ability to detect internal bodily sensations; interoceptive sensibility, which reflects the subjective evaluation or confidence in recognizing these internal bodily sensations; and interoceptive awareness, which pertains to metacognitive awareness of one's interoceptive abilities. Functionally, interoceptive awareness points out bodily needs, such as the need

to drink or to eat, and provides information on emotional state (Cali et al., 2015). Individual interoceptive accuracy is commonly assessed as the ability to feel one's own heartbeat via behavioural tasks (R. Schandry, 1981) while, interoceptive sensibility, that is the subjective beliefs about interoceptive signals, is measured via self-reported questionnaires (Garfinkel et al., 2015). Finally, interoceptive awareness is commonly assessed by comparing interoceptive accuracy and sensibility. Importantly, research shows significant declines in both interoceptive accuracy (Khalsa et al., 2009) and interoceptive sensibility (Khalsa et al., 2009; Murphy et al., 2018) declines with age.

Research on young individuals suggests that interoception modulates the online multisensory integration processes (Tsakiris et al., 2011) underlying several types of body representations. Multisensory integration refers to the brain's ability to combine information from different sensory modalities (e.g., visual, auditory, tactile) to form a coherent representation of the body and the surrounding environment (Ernst & Bühlhoff, 2004). A notable example of this process is the representation of the peripersonal space (Ardizzi & Ferri, 2018), the area immediately surrounding the body, where interactions with objects and other individuals take place. The peripersonal space representation is shaped by multisensory integration (Serino, 2019a), as the brain combines visual, tactile, and proprioceptive inputs to establish a safety margin for action and interaction. With aging, disruptions in multisensory integration can lead to difficulties in spatial orientation and motor coordination (Chepishcheva, 2023). In older adults, altered multisensory processes are associated with an increased risk of falls (Chepishcheva, 2023a; Mahoney, et al., 2019) and diminished multitasking abilities (Kuehn et al., 2018), further impacting overall mobility and daily functioning.

Moreover, interoception seems to be relevant also for tactile perception (Al et al., 2020) and sensorimotor abilities, such as mental rotation of body parts (Raimo et al., 2021). Mental rotation of body parts involves the ability to mentally visualize and manipulate the position of one's own limbs or other body segments and is essential for planning movements and interacting with the environment. These processes are closely linked to body image, which refers to the perception, thoughts, and feelings about one's own body. Body image is not only shaped by external sensory inputs (e.g., visual and tactile feedback) and motor experiences but also by interoceptive signals, which provide crucial information about the internal state of the body (Ainley et al., 2012). This interplay between interoception and body image (Badoud & Tsakiris, 2017) highlights the importance of internal bodily signals in constructing a coherent and adaptive sense of self. Despite growing evidence in specific areas, systematic investigations into the impact of interoception on multisensory processes and body representation in healthy older adults remain scarce. Previous literature suggests that interoceptive deficits in aging not only affect internal bodily awareness (Khalsa et al., 2009; Murphy et al., 2018) but also disrupt the integration of multisensory signals (Mahoney, Cotton, Verghese, et al., 2019)

necessary for effective interaction with the environment. This underscores the importance of interoception as a central mechanism underlying age-related declines in daily function activity. However, while evidence points to these connections, systematic investigations into how interoceptive deficits specifically impact multisensory integration and, consequently, functional capacity in healthy older adults remain scarce. This gap in the literature highlights the need for further research to better understand the precise role of interoception in age-related declines in functional capacity and overall well-being.

The present study has two primary aims. First, it investigates whether early changes in interoception, which influence bodily processes, can reliably predict declines in daily life functioning. Second, it aims to produce a battery of selected tests assessing specific aspects of interacting dimensions, such as interoceptive states and their awareness, multisensory processes, and exteroceptive body representations. The tests included in the battery have been selected based on their accuracy in predicting changes in daily life functioning in healthy elderly populations. Using a two-step machine learning approach, we evaluate how the interaction between interoception and exteroceptive body representation contributes to daily functioning, with the purpose of identifying key predictors that can inform timely, user-centred interventions. These interventions, tailored to the needs and characteristics of users, could help slow down the initial stages of physical decline and promote healthier aging.

Given the established link between interoception and emotional processing (Critchley & Garfinkel, 2017; Greenwood & Garfinkel, 2025; Kipping et al., 2024), we expect that interoceptive measures will predict specific aspects of daily functioning, particularly those related to emotional regulation and body perception. Additionally, considering the interaction between interoception and age-related bodily changes, we hypothesize that interoceptive parameters, when combined with exteroceptive body representation measures, will reveal how these dimensions interact to predict physical functioning and overall body capacity. Specifically, we aim to explore how the interplay between interoception and exteroceptive body representation contributes to daily functioning, highlighting their combined role in shaping functional outcomes and well-being in older adults. By focusing on the interaction between interoception and exteroceptive body representation, this study aims to provide a comprehensive understanding of how these dimensions jointly contribute to daily functioning in older adults, offering new insights into strategies for supporting active aging.

2. Methods and materials

2.1 Participant

Sixty right-handed, healthy volunteers (40 female; aged 21–87, $M = 48.58$, $SD = 18.17$), participated in the study after providing written informed consent. Younger adults were recruited through an online questionnaire, while older adults were recruited from Uni Tre Associazione Nazionale delle Università della Terza Età (National Association of Universities of the Third Age) – Chieti (Italy). Their level of education ranged from 8–24 years ($M = 15.76$ years, $SD = 3.6$ years). Cognitive function was assessed using the Mini-Mental State Examination (MMSE)(Folstein et al., 1975; Magni et al., 1996), the Montreal Cognitive Assessment (MoCa)(Carson et al., 2018; Nasreddine et al., 2005) and the Cognitive Estimation Test (CET)(Della Sala et al., 2003; MacPherson et al., 2014; O’Carroll et al., 1994). Individuals who had a MMSE and/or MoCa score that was lower than 26 were excluded. No participant had a history of neurologic, general medical or psychiatric conditions and/or medical conditions that could potentially affect cognitive functioning (e.g., Alzheimer’s disease, multiple sclerosis, and Parkinson’s disease). The experimental protocol was approved by the Institutional Ethics Committee at the University G. d’Annunzio, Chieti-Pescara and it was performed in compliance with Declaration of Helsinki’s ethical principles.

2.2 Experimental procedure

Participants completed the SF-36 Health Survey(Apolone & Mosconi, 1998; Brazier et al., 1992) a self-report questionnaire containing 36 items. It measures health on eight multi-item dimensions, covering functional status, well-being, and overall evaluation of health(Brazier et al., 1992). Then, to collect physiological data, participants were asked to rest for 5 minutes with eyes open while watching at a fixation cross at the centre of a computer screen and letting their mind wander(Raichle et al., 2001). No specific instruction on breathing was given. During this period, electrocardiogram (ECG), and respiratory signals were simultaneously recorded. To this purpose, 3 ECG electrodes (Ag/AgCl) were placed in a 3-lead configuration: two electrodes were positioned on the left side and right side of the participant’s lower abdomen, and another electrode was located underneath the right collarbone; respiratory belt was used to recorded respiratory signals. The cardiac and respiratory signals were continuously recorded with a BIOPAC MP160 System (BIOPAC System, Inc., Goleta, CA, USA) (low-pass filter: 35 Hz; high-pass filter: 0.05 Hz; notch filter: 50 Hz; sampling rate: 2000 Hz) using the AcqKnowledge software (version 5.0.5, BIOPAC System, Inc., Goleta, CA, USA). Finally, each participant completed a battery of tasks and questionnaires evaluating

interoceptive bodily dimensions and different aspects of body representation(Pasciucco et al., 2025). These measures were selected based on their relevance to bodily awareness and their ability to capture age-related changes in multisensory integration and body perception, as outlined in the study's primary aims.

2.3 Interoceptive Bodily Dimensions

2.3.1 Interoceptive Accuracy

Interoceptive accuracy refers to the accuracy in detecting internal bodily sensations(Garfinkel et al., 2015). Two tasks determined cardiac interoceptive accuracy: the Heartbeat Detection task, also known as the Tapping or Tracking task(Brener & Ring, 2016; McFarland RA., 1975), and the Heartbeat Counting task(R. Schandry, 1981). In the Heartbeat Detection task participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. The task consisted of two time periods, each lasting 2 minutes, with a pause between them. To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). The Heartbeat Counting task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). The task consists of four different time periods: 25 seconds, 30 seconds, 45 seconds, and 100 seconds (Pollatos et al., 2008). These time periods are presented in a random order to avoid predictable patterns. The task begins with a 10-second introductory phase to allow participants to settle into the task. Each period is presented separately, with a pause between each trial. Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats(Koch et al., 2014).

2.3.2 Interoceptive Sensibility

Interoceptive Sensibility is the subjective account of experiencing internal bodily sensations(Critchley & Garfinkel, 2017). This dimension can be assessed using subjective measures that index both the individual's confidence in their interoceptive ability and their interoceptive feelings (Garfinkel et al., 2015). We evaluated this dimension through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d) and the

Heartbeat Counting task (Con-c). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

We also used two self-report questionnaires: the Body Perception Questionnaire (BPQ)(Poli, Maremmani, et al., 2021; Porges, 1993) and the Multidimensional Assessment of Interoceptive Awareness (MAIA) (Mehling et al., 2012). The BPQ generally evaluates body awareness and autonomic symptoms. From the BPQ we obtained a score for each subscale: the body awareness (BOA) that consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) that is involved in regulating the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), includes items related to subdiaphragmatic issues. The MAIA generally evaluates multiple dimensions of interoception. From the MAIA we obtained a score for each subscale: Noticing (1M), Not-Distracting (2M) Not-Worrying (3M) Attention Regulation (4M) Emotional Awareness (5M) Self-Regulation (6M) Body Listening (7M) Trusting (8M).

2.3.3. Interoceptive Awareness

Interoceptive Awareness is the metacognitive awareness of interoceptive accuracy and refers to the correspondence between objective interoceptive accuracy and subjective confidence report(Garfinkel et al., 2015; Suzuki et al., 2013). We quantified the participant's awareness by comparing the accuracy and the sensibility in both the Heartbeat Detection task (Aw-d) and the Heartbeat Counting task (Aw-c).

2.4 Body Image

Body Image refers to our subjective experience of the physical structure of our body in terms of its size, shape, and physical composition(Longo, 2016). This dimension was evaluated through the Photographic Figure Rating Scale (PFRS) task, adapted from the study by Naor-Ziv et al.(Naor-Ziv et al., 2020). Participants were shown a series of ten silhouette images representing a wide range of body sizes, ranging from extremely thin to extremely obese. The ten images were calibrated with specific Body Mass Index (BMI) value, ranging from Image 1 with a BMI of 16 to Image 10 with a BMI of 40(Pasciucco et al., 2025; Swami et al., 2008). In more details: Image 1 (BMI = 16), Image 2 (BMI = 18), Image 3 (BMI = 21), Image 4 (BMI = 23), Image 5 (BMI = 25), Image 6 (BMI = 28), Image 7 (BMI = 31), Image 8 (BMI = 33), Image 9 (BMI = 36), and Image 10 (BMI = 40). This

calibration provided a standardized representation of body sizes in the scale. Each participant viewed the series of ten images twice: once in ascending order (from thinnest to heaviest) and once in descending order (from heaviest to thinnest). Participants were instructed to select a single image based on their perceived similarity to their own current physique. Based on the height and weight of each participant, we calculated the real BMI (BMI R); from this task, we quantified the mean Body Mass Index (BMI) reflecting each participant's actual physique (A), and the discrepancies between these means and the participants' actual BMI (R), denoted as ΔAR (A-R).

2.5 Spatial Tactile Acuity

Spatial Tactile Acuity refers to the ability to precisely perceive the location and quality of touch (Harvie et al., 2018). This dimension was evaluated through the two-point discrimination (2PD) task, which assesses the ability of participants to identify two closely spaced points on a small area of the skin and measures the accuracy of their discrimination skills (Weber, 1996). We compared two body parts chest and arm used as targets with the neck used as reference (Spitoni et al., 2015). From this task, we quantified the correct response for the two target body parts, chest (C-che) and arm (C-arm).

2.6 Body Structural Representation

Body Structural Representation (BSR) refers to knowledge about the topological organization of bodies, outlining how different body parts interrelate within a spatial configuration, focusing on the spatial positioning of each body part related to others (Longo, 2016). This dimension was evaluated through the Finger Localization Task (Benton, 1983), which requires participants to identify and differentiate stimulated fingers in three different conditions. Participants were seated in front of a table with their hands placed on the table, palms up, and their fingers extended and slightly separated. The test consisted of three tasks, with ten trials for each hand in each task. In the first task (a), participants were required to identify whether the experimenter touched a finger on their left hand or their right hand. The second task (b) involved participants identifying which finger on their left hand or right hand was touched by the experimenter, with their hands hidden from view. Finally, in the third task (c), participants had to identify pairs of fingers on their left hand or right hand that were touched by the experimenter, while their hands remained hidden from view. Participants indicated their responses by pointing to the correct answer on an outline of a human hand, correct responses were recorded for each trial, and the maximum total score was 60 (Costantini et al., 2020; Fotia et al.,

2022). We focused on the third condition, and we calculated the accuracy and included the score of correct responses (HIT) as a variable.

2.7 Multisensory Integration

Multisensory Integration refers to the process by which inputs from two or more sensory modalities are combined by the nervous system to form a stable and coherent percept of the world (Yau et al., 2015). This dimension was evaluated through the Multisensory Integration (MSI) task aiming at investigating the integration of visual, auditory, and tactile stimuli in participants' perception. Visual stimulation was achieved by incorporating a LED light placed inside a box. Tactile stimulation was provided using a constant-current electrical stimulator (Digitimer DS7A), delivering electrical pulses via electrodes attached to the participant's right middle finger. The auditory stimulation was introduced by playing brief auditory beeps. The experiment consisted of a total of 180 trials including one of six different conditions: visual-only (V), tactile-only (T), auditory-only (A), visuo-tactile (VT), audio-visual (AV), and audio-tactile (AT). These conditions were presented in a randomized order, with 30 trials assigned to each condition. Participants were instructed to respond promptly using a foot pedal response pad positioned under their right foot. They were asked to press the pedal as quickly as possible upon perceiving any stimulus presented during the task (Mahoney et al., 2015). For each multisensory pair – audio-visual (AV), audio-tactile (AT) and visuo-tactile (VT) - the analysis involved calculating the area-under-the-curve (AUC) subtended by the distribution of reaction times to multisensory stimuli as compared to the distribution of reaction times to unimodal stimuli. Hence, AUC-av, AUC-at and AUC-vt represent a proxy of the magnitude of multisensory integration for audio-visual, audio-tactile and visuo-tactile stimuli, respectively (Mahoney, Cotton, & Verghese, 2019).

2.8 Multisensory Temporal Resolution

Multisensory Temporal Resolution refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. This principle highlights the critical role of temporal proximity in influencing the nervous system's integration of diverse sensory information (Sarko et al., 2012).

This dimension was evaluated through the Simultaneity Judgment (SJ) task, which aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Auditory stimuli were delivered through headphones and consisted of a 3,500-Hz pure tone lasting 30ms. Tactile stimuli were administered using two constant-current

electrical stimulators (Digitimer DS7A), which controlled two pairs of neurological electrodes attached to the participant's right and left middle fingers. Tactile stimuli were single, constant voltage, rectangular monophasic pulses lasting 100 μ s. During the task, participants were blindfolded and comfortably seated at a table, with their index fingers resting on separate keys of a response box. The intensity of the stimuli was adjusted to each participant's detection threshold, set at 100% for both auditory and tactile stimuli. In each trial, two stimuli were presented in opposite hemispaces, with stimulus pairs randomly interleaved at various stimulus onset asynchronies (SOAs): ± 450 , ± 350 , ± 200 , ± 120 , ± 70 , ± 40 , ± 15 , and 0 ms. Participants had to indicate whether the two stimuli were presented simultaneously or not using the response box. The AT-SJ task comprised two blocks, each consisting of 120 trials, resulting in a total of 240 trials (16 trials per SOA). The association between the side of presentation (right or left) and the modality (auditory or tactile) was balanced across trials, and the stimulus-response association was counterbalanced between blocks. Two parameters are usually derived from this task: the point of subjective equality (PSE), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the 'just noticeable difference' (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed (Binder, 2015).

2.9 Peripersonal Space

Peripersonal Space refers to the space surrounding the body where the integration of stimuli on the body and from the external environment is facilitated (Rabellino et al., 2020). This dimension was evaluated through the Peripersonal Space (PPS) task (Canzoneri et al., 2012; Di Cosmo, Costantini, Spadone, et al., 2021; Di Cosmo et al., 2018), which allows evaluating the individual's boundaries of the peripersonal space by assessing the optimal temporal interval for the integration of tactile and auditory stimuli (Ferri et al., 2015; Spadone et al., 2021). During the experiment, the participants were blindfolded and seated comfortably at a table with their right hand resting on the palm. The equipment used consisted of headphones and a constant-current electrical stimulator (Digitimer DS7A) that controlled a pair of electrodes attached to the participant's right middle finger. Each experimental trial involved the presentation of a looming sound along with a tactile stimulus. The tactile stimulus was delivered at five different time delays from the onset of the auditory stimulus (D1: 300 ms, D2: 800 ms, D3: 1500 ms, D4: 2200 ms, and D5: 2700 ms). Tactile stimulation could also be delivered during the silent periods preceding the presentation of the sound (D0: -700 ms). The remaining trials were catch trials, involving only auditory stimulation. The experiment consisted of a total of 80 trials, including 50 post-trials (10 for each delay), 10 pre-trials, and 20 catch trials. The participants were

instructed to respond as quickly as possible to the tactile stimulus by pressing a button on a response box with their left index finger. They were required to ignore the auditory stimulus. After each trial, there was an intertrial interval of 1000 ms to allow for rest and preparation for the next trial (Ardizzi & Ferri, 2018; Canzoneri et al., 2012; Di Cosmo, Costantini, Spadone, et al., 2021). To estimate the individual boundary of the peripersonal space (PPS), a psychometric function is fitted to the RT data. The PSE of the psychometric function is taken as a proxy of the peripersonal space boundary, and we included PSE as a variable.

2.10 Temporal Tactile Acuity

Temporal Tactile Acuity refers to the ability to perceive and discriminate temporal aspects of tactile stimuli. It involves the capacity to detect and distinguish temporal characteristics of sensations related to touch (Laasonen et al., 2001). This dimension was evaluated through the Temporal Order Judgment. In a typical Temporal-Order Judgment (TOJ) task, participants are tasked with determining the order of two tactile stimuli presented sequentially to their left and right hands. When the hands are in an “uncrossed” position (toju), participants can rely on tactile and proprioceptive cues related to their body posture, utilizing a body-centred reference frame (Heed et al., 2014). During TOJ, participants were blindfolded and seated at a table with their hands placed palm down on the table surface. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli, (i.e., stimulus onset asynchrony SOA), was randomly assigned from 22 intervals. In the uncrossed condition, it ranged from -450 to 450 ms (± 450 , ± 300 , ± 200 , ± 150 , ± 100 , ± 75 , ± 50 , ± 40 , ± 30 , ± 15 , ± 5 ms). Negative and positive intervals indicated whether the left or right hand was stimulated first. The inter-trial intervals varied between 2000 and 4000 ms. Each condition comprised 176 trials, with eight trials per SOA (Ferri et al., 2016). Tactile stimuli were delivered using two constant-current electrical stimulators (Digitimer DS7A), which controlled pairs of neurological electrodes attached to the dorsal surface of the middle fingers. The stimuli were supra-threshold vibrotactile stimuli oscillating at 100 Hz, with a total duration of 30ms. They were instructed to make two-alternative forced-choice judgments regarding the order of stimulation by pressing the button under the index finger of the hand they believed was stimulated earlier or later than the other. The two response strategies (earlier and later) were counterbalanced. Trials with response times exceeding 3000 ms or without a response were re-presented at the end of the corresponding block, ensuring an equal number of trials across all experimental conditions. No feedback was provided to the participants. From this task, we quantified the JND (JND-toju), as a measure of precision, and the proportion of correct responses (Azañón et al., 2016). The JND-toju

represents the smallest interval at which the participants can reliably decide which sensory input of the two presented was first(Kostaki M. & Vatakis A., 2018).

2.11 Sensorimotor functions

Touch remapping

To perceive the location of touch in space, the brain combines information about touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands(Azañón et al., 2016). This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (tojc)(Ferri et al., 2016). In crossed condition participants were instructed to cross their arms over their wrists. The two possible arm positions (right over left and vice versa) were counterbalanced across participants, and the order was randomly assigned to each participant. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli ranged from -900 to 900 ms (± 900 , ± 600 , ± 400 , ± 300 , ± 200 , ± 150 , ± 100 , ± 80 , ± 60 , ± 30 , ± 10 ms). From this task, we measured the following variables: the JND (JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first(Kostaki M. & Vatakis A., 2018) and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions(Ferri et al., 2016). SC-toj is a global indicator of differences, which provides an overarching measure of the divergence between the two conditions and assess increases in judgment reversals resulting from the arm-crossing manipulation(Wada et al., n.d.).

Laterality Judgment Task

The Laterality Judgement Task (LJT) is designed to assess participants' ability to mentally rotate the presented hand images and accurately judge the lateral orientation of presented hand images(Mibu et al., 2020). In this task, grey-scale pictures depicting the dorsal view of both right and left hands are presented individually on a computer screen. The hand images are displayed in six different clockwise orientations: upright 0° , 60° , 120° , 180° , 240° , and 300° , with the upright orientation representing the hand with the fingers pointing upwards. Participants were seated in front of a computer screen at approximately 40 cm. Each trial commences with the presentation of a central fixation cross, which remains on the screen for 500 milliseconds to ensure participants' attention is focused. Following the

fixation cross, a hand image is presented at the centre of the screen. The hand images can represent either a left or a right hand. During the task, participants were instructed to judge the laterality (left or right) of the observed hand image as accurately and quickly as possible. They have a maximum response time window of 4000 milliseconds to provide their judgment. Participants use their left and right index fingers to press designated response keys that correspond to their judgment of the hand's laterality. The left key is pressed for a judgment of "left hand," while the right key is pressed for a judgment of "right hand"(Ferri et al., 2011) The LJT comprises a total of 144 trials, with each orientation condition being presented 12 times. We calculated slopes, which reflect the efficiency of the neural mechanism underlying the mental rotation process: a smaller slope indicates higher neural efficiency in mental rotation(Christova et al., 2008). We quantified slopes for both hands, indicated as Mental Rotation Efficiency for the left hand (MRE-lh) and the right hand (MRE-rh), illustrating the efficiency of the respective mental rotation processes(Ferri et al., 2011).

3. Data analysis

3.1 Physiological measurements

ECG data were processed using custom MATLAB code (R2021b, MathWorks Inc, Natick, MA, USA). R-peaks were detected with the Pan-Tompkins algorithm(Pan & Tompkins, 1985). To measure Heart Rate Variability (HRV), the time series of the distance between consecutive R-peaks (tachogram) was computed. Kubios software (Kubios HRV Scientific 4.1.0)(Tarvainen et al., 2014) was employed to pre-process the tachogram and extract mean HR and frequency-domain HRV features of interest. The ECG tachogram was interpolated at 4 Hz. Frequency-domain analysis utilized the Fast Fourier Transform (FFT)-based Welch's periodogram applied to the detrended RR series. We calculated mean heart rate (HR - bpm, the average number of heartbeats in one minute), High Frequency (HF: .15-.4 Hz) log power (log ms²/Hz, the log-transformed power of HF band) and Low Frequency/High Frequency ratio (LF/HF). Respiratory data were processed using custom MATLAB scripts (R2021b, MathWorks Inc, Natick, MA, USA). Respiratory phases were detected following a validated procedure(Grund et al., 2022) and respiratory cycle was defined as the interval from one inhalation onset (referred to as "trough") to the subsequent trough. We calculated Breath Frequency (breaths/min).

Mean heart rate (HR), high frequency (HF), the ratio between low frequency and high frequency (LF/HF) and Breath Frequency were included these parameters as variables.

A detailed description of all experimental tasks and questionnaires used to assess interoceptive, exteroceptive, and multisensory bodily dimensions is provided in the Table 1

3.2 Interoceptive Bodily Dimensions

3.2.1 Interoceptive accuracy

To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). The analysis involves categorizing the tapping responses based on the participant's heart rate (HR) (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). Three categories are used: $HR < 69.75$, $69.75 < HR < 94.25$, and $HR > 94.25$. For each recorded heartbeat, the difference between the tapping time and the nearest R-peak is calculated. If the HR falls into one of the predefined categories, the tapping response within a specific time window is considered correct. The number of correct tapping responses is tallied for each HR category. The total correct responses for $HR < 69.75$, $69.75 < HR < 94.25$, and $HR > 94.25$ are denoted as `corr_69`, `corr_betw`, and `corr_94`, respectively. The task accuracy is then calculated as follows: $accuracy = 1 - (|recorded_heartbeats - (corr_69 + corr_betw + corr_94)| / recorded_heartbeats)$ (Zaccaro et al., 2022).

The Heartbeat Counting task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats (Koch et al., 2014). The participants' interoceptive accuracy score was computed according to the formula: $Accuracy = 1/4 \sum [1 - (|recorded\ heartbeats - counted\ heartbeats| / recorded\ heartbeats)]$.

3.2.2 Interoceptive sensibility

We evaluated the sensibility through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

The similar procedure was used to evaluate the level of confidence after the performance in the Heartbeat Counting task (Con-c).

Interoceptive sensibility was also assessed through The Body Perception Questionnaire (BPQ) (Poli, Maremmani, et al., 2021; Porges, 1993) and Multidimensional Assessment of Interoceptive

Awareness (MAIA)(Multidimensional Assessment of Interoceptive Awareness (MAIA) Valutazione Multidimensionale Della Consapevolezza Interocettiva (MAIA, Dalla Sigla Inglese), n.d.).

3.2.3 Interoceptive awareness

The awareness was calculated comparing the accuracy and the confidence through the absolute difference between the rescaled (min-max normalization) measures of interoceptive accuracy and confidence(Mattioni et al., 2024); both in Heartbeat Detection task (Aw-d) and Heartbeat Counting task (Aw-c).

3.3 Body Image

Based on the height and weight of each participant, we calculated the real BMI (BMI R). Based on the data collected from the participants' rankings on the Photographic Figure Rating Scale (PFRS), we calculated the mean BMI for participant's perceived actual physique (BMI A). These means were derived from the participants' rankings of the silhouette images on the PFRS. We also calculated the differences between the participants' real BMI (BMI R) and the mean BMI A (ΔAR), as the difference between BMI A and BMI R.

3.4 Spatial Tactile Acuity

From Two Point discrimination task (2PoD) we calculated the accuracy as percentages of trials in which participants provided correct responses for each condition and included the score of correct responses on chest (C-che) and arm (C-arm) as a variable.

3.5 Body Structural Representation

Considering the third condition of the Finger Localization task (FLT), we calculated the accuracy and included the score of correct responses (HIT) as a variable.

3.6 Multisensory Integration

To analyse the data collected during the Multisensory Integration task (MSI), several steps were followed. First, the reaction time (RT) data were organized by sorting them according to the experimental condition: A, T, V, AT, AV, VT. Each trial was represented in a separate row, with the

corresponding RT recorded in the cells. The next step involved calculating the cumulative distribution frequency (CDF) for each experimental condition, which involved determining the proportion of RTs falling within each time bin. The CDF values were then summed across the time bins to create a cumulative probability distribution for each condition. Finally, the actual and predicted CDFs were compared to evaluate the presence of multisensory integration. This was done by subtracting the predicted CDF, obtained by summing the individual unimodal CDFs, from the actual CDF. Positive values indicated integration of the unimodal stimuli and a violation of the Race Model Inequality (RMI). The analysis also involved calculating the area-under-the-curve (AUC) for the violated percentile range to quantify the magnitude of multisensory integration.

3.7 Multisensory Temporal Resolution

We calculated the ‘just noticeable difference’ (JND-sj) from Simultaneity Judgment (SJ): this parameter reflecting the subject’s sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed (Binder, 2015). The response data were analysed using a Gaussian distribution.

3.8 Peripersonal Space

To estimate the individual boundary of the peripersonal space (PPS), we performed an analysis on reaction time (RT) data. The Spearman-Kärber (SK) method was used for this analysis. The Spearman-Kärber (SK) method was employed to estimate the point of subjective equality (PSE) of the psychometric function (Bausenhardt et al., n.d.; Miller & Ulrich 2001 *Psychometric Functions*, n.d.). The SK method involves fitting a psychometric function to the RT data, which relates the probability of a correct response to tactile distance. The PSE is then obtained as the midpoint of the psychometric function. This method has been widely used to estimate sensory thresholds and perceptual boundaries in various experimental contexts (Ferroni et al., 2022; Masson et al., 2021). By applying the SK method to our dataset, we obtained individual PSE values.

3.9 Temporal Tactile Acuity

From Temporal Order Judgment (TOJ, uncrossed hands), we measured the JND (JND-toju) which represents the smallest interval at which participants can reliably determine which of the two

presented sensory inputs came first(Kostaki M. & Vatakis A., 2018). The mean response times (RT) and participant responses were calculated by considering the temporal distance between stimuli (SOA). To analyse the experimental data, a fitting function was applied using a normal distribution model.

3.10 Sensorimotor functions

Touch remapping

From Temporal Order Judgment (TOJ, crossed hands), we measured the JND (JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first. The mean response times (RT) and participant responses were calculated by considering the temporal distance between stimuli (SOA). To analyse the experimental data, a fitting function was applied using a normal distribution model.

To quantify the overall difference between the 'Cross' and 'Uncross' conditions, the cumulative sum of differences between the fitted models was computed. This yielded a global indicator of difference, denoted as Sum of Confusion (SC) provided an overarching measure of the divergence between the two conditions(Ferri et al., 2016; Wada et al., 2014).

Laterality Judgment Task

In Laterality Judgment Task (LJT) both accuracy and response speed are essential performance measures. We calculated slopes, which reflect the efficiency of the neural mechanism underlying the mental rotation process: a smaller slope indicates higher neural efficiency in mental rotation(Christova et al., 2008). We quantified slopes for both hands, indicated as Mental Rotation Efficiency for the left hand (MRE-lh) and the right hand (MRE-rh).

Table 1 Summary of participants' demographic characteristics, cognitive screening scores (MMSE, MoCA, CET), and scores for all interoceptive, exteroceptive, and multisensory variables included in the study.

	Young early adulthood N=25		Middle adulthood N= 13		Old age N=22	
	M=13	F=12	M=2	F=11	M=5	F=17
	MEAN	SD	MEAN	SD	MEAN	SD
Age	30,12	5,98	50,62	6,44	68,36	6,69
SF-36 Short Form Health Survey						
Scales	MEAN	SD	MEAN	SD	MEAN	SD
Physical Functioning	98,00	4,56	91,15	13,56	83,64	13,02

Role Limitations due to physical health problems	84,00	30,52	73,08	34,55	80,68	33,57
Role Limitations due to personal/emotional problems	66,67	43,03	61,54	40,47	87,88	30,07
Energy/Fatigue	54,20	13,59	56,54	21,54	61,14	17,52
Emotional Well-Being	64,80	18,48	65,54	19,63	68,55	19,37
Social Functioning	72,50	25,52	65,38	17,79	78,41	19,74
Bodily Pain	84,00	20,05	70,58	20,90	78,30	16,64
General Health	70,40	21,93	65,38	17,85	60,68	14,00
Cognitive screening						
Questionnaire	MEAN	SD	MEAN	SD	MEAN	SD
MMSE Mini-Mental State Examination	26,70	0,63	27,26	0,73	27,68	1,20
MoCa Montreal Cognitive Assessment	28,20	1,26	26,85	0,99	27,27	1,35
CET Cognitive Estimation Test	14,64	3,08	13,69	2,25	13,23	3,41
Physiological measures						
Measures	MEAN	SD	MEAN	SD	MEAN	SD
Breath Frequency	14,37	3,80	14,76	2,05	17,15	4,04
Mean HR	73,58	8,04	72,99	9,12	66,65	8,66
HF High Frequency	5,77	1,04	4,88	0,86	4,38	1,16
LF/HF Ratio between low frequency and high frequency	0,64	0,19	0,42	0,21	0,38	0,22
MAIA Multidimensional Assessment of Interoceptive Awareness						
Scales	MEAN	SD	MEAN	SD	MEAN	SD
M1 Noticing scale	3,18	0,93	1,98	1,14	2,47	1,39
M2 Not-Distracting scale	2,36	0,62	2,85	0,88	1,79	0,91
M3 Not-Worrying scale	2,53	1,04	2,56	1,02	2,33	0,86
M4 Attention Regulation scale	2,99	1,02	2,57	0,90	2,94	1,08
M5 Emotional Awareness scale	3,42	0,94	3,25	0,90	3,43	1,14
M6 Self-Regulation scale	2,61	1,13	2,60	1,11	2,91	1,10
M7 Body Listening scale	2,65	1,10	2,44	1,44	2,70	1,50
M8 Trusting scale	3,19	0,99	3,46	1,15	3,92	1,14
BPQ Body Perception Questionnaire						
Scales	MEAN	SD	MEAN	SD	MEAN	SD
BPQ_BOA Body Awareness	16,32	3,69	13,38	4,35	12,82	3,25
BPQ_SUP Supradiaphragmatic Reactivity	10,60	2,92	10,23	3,00	11,00	2,41
BPQ_BOA/SUB Body Awareness/Subdiaphragmatic reactivity	15,44	2,83	14,15	4,16	12,82	2,81
Interoceptive Tasks						
Variables	MEAN	SD	MEAN	SD	MEAN	SD
Acc-d Accuracy in heartbeat detection task	0,77	0,16	0,82	0,13	0,70	0,21
Con-d Confidence in heartbeat detection task	5,17	1,63	6,23	2,01	6,07	1,85

Aw-d Awareness in heartbeat detection task	0,73	0,22	0,82	0,18	0,70	0,26
Acc-c Accuracy in heartbeat counting task	0,76	0,18	0,78	0,11	0,66	0,20
Con-c Confidence in heartbeat counting task	6,57	1,21	6,65	1,22	6,99	1,24
Aw-c Awareness in heartbeat counting task	0,69	0,18	0,74	0,23	0,69	0,16
LJT Laterality Judgment Task						
Variables	MEAN	SD	MEAN	SD	MEAN	SD
MRE-rh Mental Rotation Efficiency – right hand	230,17	105,00	246,76	119,55	270,90	174,90
MRE-lh Mental Rotation Efficiency – left hand	223,28	132,15	224,25	141,00	234,11	116,18
PPS Peripersonal Space Task						
Variable	MEAN	SD	MEAN	SD	MEAN	SD
PSE-pps Point of Subjective Equality	1361,38	515,74	1486,01	417,29	1507,82	561,59
SJ Simultaneity Judgment Task						
Variable	MEAN	SD	MEAN	SD	MEAN	SD
JND-sj Just Noticeable Difference	109,41	34,19	186,04	109,84	-3285,65	15495,79
TOJ Temporal Order Judgment Task						
Variables	MEAN	SD	MEAN	SD	MEAN	SD
JND-tojun Just Noticeable Difference - Uncross condition	54,65	27,39	111,88	92,86	150,02	207,32
JND-tojer Just Noticeable Difference – Cross condition	64,17	38,34	165,08	280,25	134,79	116,85
SC Sum of Confusion	70,63	88,84	72,94	111,50	115,89	134,24
PFRS Photographic Figure Rating Scale						
Variable	MEAN	SD	MEAN	SD	MEAN	SD
ΔAR discrepancies between A and the participants BMI	1,58	3,84	2,30	4,07	3,24	4,27
FLT Finger Localization Task						
Variable	MEAN	SD	MEAN	SD	MEAN	SD
HIT Correct response	0,97	0,08	0,98	0,04	0,93	0,10
2PD Two Point Discrimination Task						
Variables	MEAN	SD	MEAN	SD	MEAN	SD
C-che Correct response for chest	0,80	0,13	0,83	0,16	0,76	0,14
C-arm Correct response for arm	0,77	0,12	0,82	0,10	0,70	0,13
MSI Multisensory Integration Task						
Variables	MEAN	SD	MEAN	SD	MEAN	SD
AUC-av Area Under the Curve audio-visual	0,21	0,19	0,17	0,16	0,20	0,20
AUC-at Area Under the Curve audio-tactile	0,21	0,17	0,12	0,17	0,23	0,24
AUC-vt Area Under the Curve visuo-tactile	0,23	0,14	0,24	0,26	0,17	0,13

4. Statistical Analysis: Machine Learning Approach

The study employed a two-step machine learning approach to investigate the contribution of interoceptive dimensions and body representations to daily functioning in active aging and explore how these dimensions interact to predict daily functioning. The aim was to identify the most predictive interoceptive measures and evaluate how the inclusion of body representation variables contributes to a more comprehensive understanding of daily functioning by capturing the interplay between internal and external bodily dimensions.

We employed Partial Least Squares Regression (PLSR), a dimensionality reduction technique effective in mitigating overfitting and handling collinearity (Pasciucco et al., 2025). The PLSR constructs regression models by projecting predictors into a lower-dimensional space of uncorrelated components, which are linear combinations of the original predictors. These components capture the most relevant information in the independent variables, enabling accurate prediction of the dependent variable while reducing model complexity. We implemented leave-one-out nested cross-validation (nCV) to optimize the hyperparameter (K, the number of uncorrelated components) and ensure robust generalization performance. In this study, a leave-one-out nCV was implemented to assess the PLSR generalization performance and the optimal number of components using the SF-36 Health Survey scale as the dependent variables: physical functioning, role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue, emotional well-being, social functioning, bodily pain and general health perceptions. In the first step, for each of them, PLSR was used to test and found the most predictive interoceptive measures resulting a total of eight models. The independent variables were the following: Acc-d, Acc-c, Con-d, Con-c, BOA, SUP, BOA/SUB, 1M-8M, Aw-d, Aw-c, Breath Frequency, mean HR, HF, LF/HF. Each model was trained and tested separately to identify the most significant interoceptive predictors for each SF-36 dimension.

The second step focused exclusively on the SF-36 scale that were significantly predicted by interoceptive measures in the previous step. In this phase, PLSR was employed to test only the significant interoceptive predictors, with the addition of body representation variables. These variables included measures of body image (ΔAR), tactile acuity (C-che, C-arm), body representation (HIT), multisensory integration (AUC-av, AUC-at, AUC-vt), multisensory temporal resolution (JND-sj), peripersonal space (PSE-pps), temporal tactile acuity (JND-toju) and sensorimotor function (JND-tojc, SC, MRE-lh, MRE-rh).

5. Results

5.1 Step 1: Predictive impact of interoceptive dimensions to daily functioning

To explore whether and to what extent different daily functioning aspects are influenced to varying degrees by the interoceptive dimensions, we ran eight models one for each SF-36 Health Survey scale: physical functioning, role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue, emotional well-being, social functioning, bodily pain and general health perceptions.

The model testing the predictive impact of interoceptive dimensions on role limitations due to physical health problems scale was significant after cross-validation (see Fig. 1a). A significant positive correlation between the actual role limitations due to physical health problems scale and the predicted role limitations due to physical health problems scale was obtained ($r = 0.41418$, $p < 0.001$). Dimensions that significantly contributed was only interoceptive sensibility (6M, corresponding to the Self-Regulation subscale).

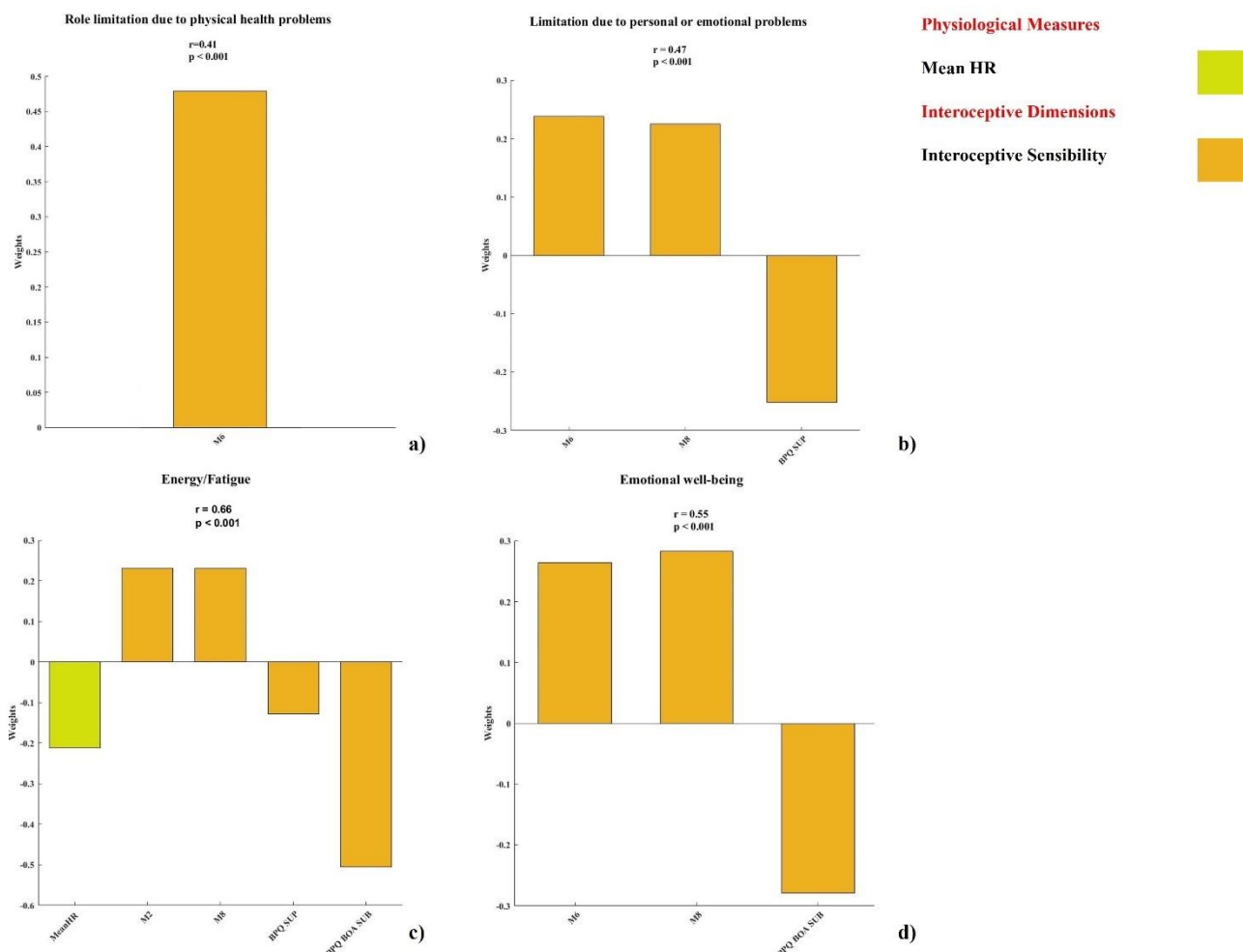


Fig. 1 Contribution of interoceptive dimensions to SF-36 Health Survey scale. PLSR out-of-sample prediction of SF-36 Health Survey scale shows significant correlations between true and predicted values (R and p values reported). (a) role limitations due to physical health problems: Regression weights for interoceptive variables (M6). (b) role limitations due to personal or emotional problems I: Weights for variables (M6, M8, BPQ-SUP). (c) energy/fatigue: Weights for variables (Mean HR, M2, M8, BPQ-SUP, BPQ-BOA/SUB). (d) emotional well-being: Weights for variables (M6, M8, BPQ-BOA/SUB). Only weights exceeding the 95% confidence interval of the null hypothesis are reported.

The model testing the predictive impact of interoceptive dimensions on role limitations due to personal or emotional problems scale was significant after cross-validation (see Fig. 1b). A significant positive correlation between the actual role limitations due to personal or emotional problems scale and the predicted role limitations due to personal or emotional problems scale was obtained ($r=0.469$, $p<0.001$). In this case as well, interoceptive sensibility was the only dimension that significantly contributed, through different aspects: specifically, 6M corresponding to the Self-Regulation subscale, 8M corresponding to the Trusting scale, BPQ-SUP corresponding to the Supradiaphragmatic reactivity scale.

The model testing the predictive impact of interoceptive dimensions on energy/fatigue scale was significant after cross-validation (see Fig. 1c). A significant positive correlation between the actual energy/fatigue scale and the predicted energy/fatigue scale was obtained ($r=0.66408$, $p<0.001$). In this case, a physiological contribution, reflected in mean heart rate (HR), synergized with contributions from different aspects of interoceptive sensibility: specifically, 2M corresponding to the Not-Distracting scale, 8M corresponding to the Trusting scale, BPQ-SUP corresponding to the Supradiaphragmatic reactivity scale, BPQ-BOA/SUB corresponding to the body awareness and the subdiaphragmatic reactivity scale.

The model testing the predictive impact of interoceptive dimensions on emotional well-being scale was significant after cross-validation (see Fig. 1d). A significant positive correlation between the actual emotional well-being scale and the predicted emotional well-being scale was obtained ($r=0.55279$, $p<0.001$). Once again, 6M, 8M, and BPQ-BOA/SUB emerged as the key aspects of interoceptive sensibility that significantly contributed, with 6M corresponding to the Self-Regulation scale, 8M to the Trusting scale, and BPQ-BOA/SUB to the body awareness and the subdiaphragmatic reactivity scale.

The model testing the predictive impact of interoceptive dimensions on physical functioning, social functioning, bodily pain and general health perceptions scale were non-significant after cross-validation.

Step 2: Predictive impact of interaction between interoceptive dimensions and body representation to daily functioning

We then evaluated how the inclusion of body representation variables, interacting with interoceptive measures, contributes to the prediction of daily functioning outcomes for the SF-36 scales that were significantly predicted by interoceptive dimensions in the previous step. Specifically, we aimed to identify which exteroceptive body representation measures, in combination with interoceptive parameters, emerge as significant predictors. Hence, we ran four separate PLSR models one for each of the following scales: role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue and emotional well-being.

For each model, the significant interoceptive predictors identified in the first step were retained: Mean heart rate (mean HR), Not-Distracting scale (2M), Self-Regulation scale (6M), Trusting scale (8M), supradiaphragmatic reactivity scale (BPQ-SUP) and the body awareness and the subdiaphragmatic reactivity scale (BPQ-BOA/SUB). Body representation variables were added including measures of body image (ΔAR - the discrepancy between perceived and actual body mass index), spatial tactile acuity (C-che – correct response on the chest; C-arm – correct response on the arm), body structural representation (HIT - accuracy in the Finger Localization Task), multisensory integration (AUC-av, AUC-at, AUC-vt – proxy of the magnitude of multisensory integration for audio-visual, audio-tactile and visuo-tactile stimuli, respectively), multisensory temporal resolution (JND-sj - just noticeable difference in simultaneity judgments), peripersonal space (PSE-pps - point of subjective equality), temporal tactile acuity (JND-toju - just noticeable difference in temporal order judgments for uncrossed hands), and sensorimotor functions (JND-tojc - just noticeable difference in temporal order judgments for crossed hands; SC - the sum of confusions; MRE-lh - mental rotation efficiency for the left hand, and MRE-rh - mental rotation efficiency for the right hand).

The model testing the predictive impact of interoceptive dimensions and body representation variables on role limitations due to physical health problems scale was significant after cross-validation (see Fig. 2a). A significant positive correlation between the actual role limitations due to physical health problems scale and the predicted role limitations due to physical health problems scale was obtained ($r = 0.58296$, $p < 0.001$). Dimensions that significantly contributed were: interoceptive sensibility (6M corresponding to the Self-Regulation subscale, BPQ-SUP corresponding to the Supradiaphragmatic reactivity scale, BPQ-BOA/SUB corresponding to the body awareness and the subdiaphragmatic reactivity scale) and body image (ΔAR corresponding to the discrepancy between perceived and actual body mass index).

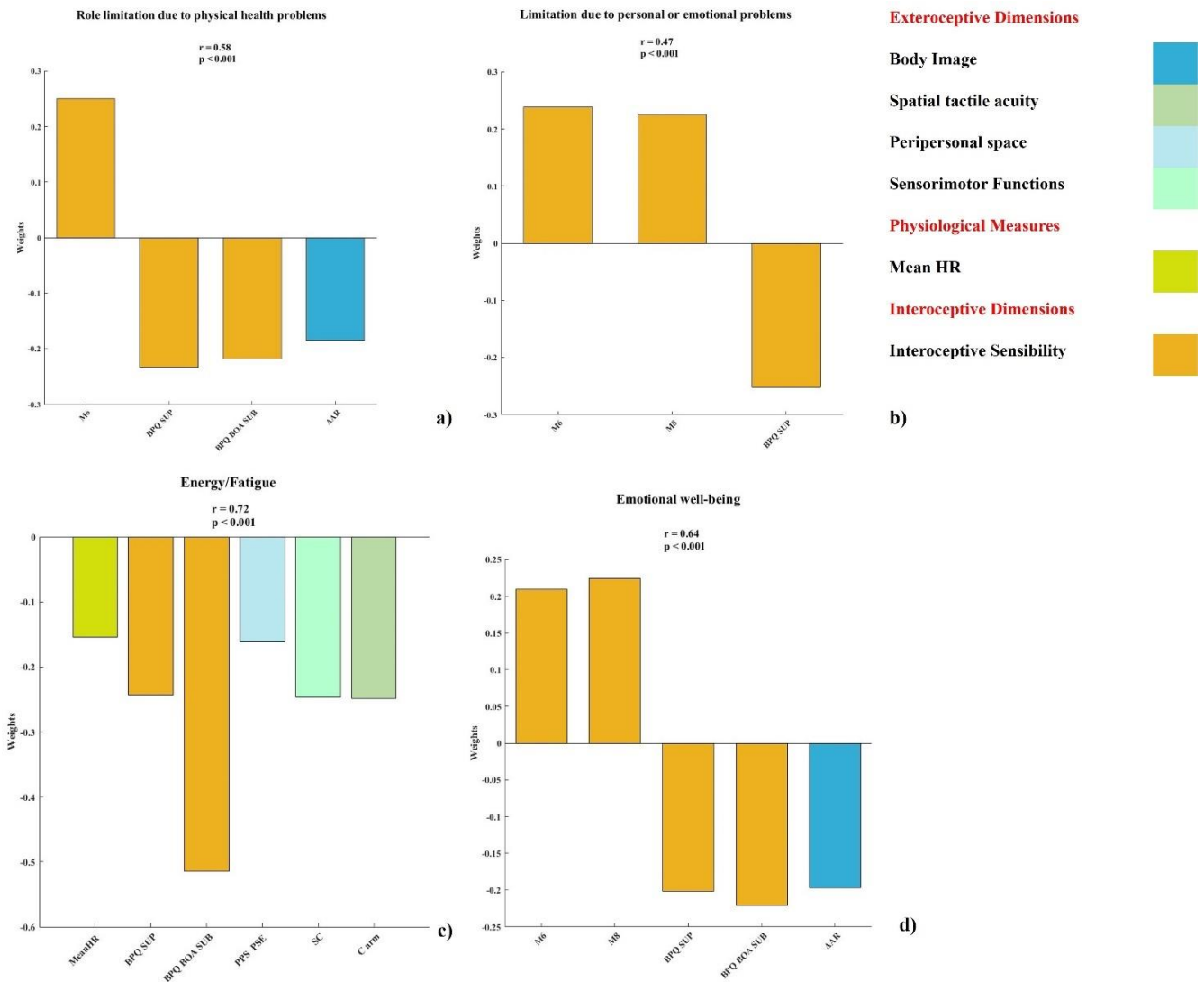


Fig. 2 Contribution of significant interoceptive dimensions and body representation variable to selected SF-36 Health Survey scale. PLSR out-of-sample prediction of SF-36 Health Survey scale shows significant correlations between true and predicted values (R and p values reported). (a) role limitations due to physical health problems: Regression weights for interoceptive variables (M6, BPQ-SUP, BPQ-BOA/SUB, Δ AR). (b) role limitations due to personal or emotional problems I: Weights for variables (M6, M8, BPQ-SUP). (c) energy/fatigue: Weights for variables (Mean HR, BPQ-SUP, BPQ-BOA/SUB, PPS PSE, SC, C-arm). (d) emotional well-being: Weights for variables (M6, M8, BPQ-SUP, BPQ-BOA/SUB, Δ AR). Only weights exceeding the 95% confidence interval of the null hypothesis are reported.

The model testing the predictive impact of interoceptive dimensions and body representation variables on role limitations due to personal or emotional problems scale was significant after cross-validation (see Fig. 2b). A significant positive correlation between the actual role limitations due to personal or emotional problems scale and the predicted role limitations due to personal or emotional problems scale was obtained ($r=0.469$, $p < 0.001$). Dimensions that significantly contributed was: interoceptive sensibility 6M corresponding to the Self-Regulation subscale, 8M corresponding to the Trusting scale, and BPQ-SUP corresponding to the Supradiaphragmatic reactivity scale. Notably, in

this model, the same interoceptive sensibility measures were confirmed as significant predictors of role limitations due to personal or emotional problems. No exteroceptive body representation variables emerged as significant predictors, suggesting that interoceptive dimensions alone were sufficient to explain this aspect of daily functioning.

The model testing the predictive impact of interoceptive dimensions and body representation variables on energy/fatigue scale was significant after cross-validation (see Fig. 2c). A significant positive correlation between the actual energy/fatigue scale and the predicted energy/fatigue scale was obtained ($r=0.71891$, $p<0.001$). Dimensions that significantly contributed were mean HR, interoceptive sensibility (BPQ-SUP corresponding to the Supradiaphragmatic reactivity scale, BPQ-BOA/SUB corresponding to the body awareness and the subdiaphragmatic reactivity scale), peripersonal space (PSE-pps corresponding to the point of subjective equality), sensorimotor function (SC corresponding to the sum of confusions) and tactile acuity (C-arm corresponding to the correct response on the arm).

The model testing the predictive impact of interoceptive dimensions and body representation variables on emotional well-being scale was significant after cross-validation (see Fig. 2d). A significant positive correlation between the actual emotional well-being scale and the predicted emotional well-being scale was obtained ($r=0.6406$, $p<0.001$). Dimensions that significantly contributed were: interoceptive sensibility (6M corresponding to the Self-Regulation subscale, 8M corresponding to the Trusting scale, BPQ-BOA/SUB corresponding to the body awareness and the subdiaphragmatic reactivity scale) and body image (ΔAR corresponding to the discrepancy between perceived and actual body mass index).

The dimension that significant predicts role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue, and emotional well-being are summarized in Tab. 1

	Role limitations due to physical health problems	Role limitations due to personal or emotional problems	Energy/Fatigue	Emotional well-being
Exteroceptive Dimensions	Body Image		Spatial tactile acuity Peripersonal space Sensorimotor functions	Body Image
Physiological Measures			Mean HR	
Interoceptive Dimensions	Interoceptive Sensibility	Interoceptive Sensibility	Interoceptive Sensibility	Interoceptive Sensibility

Tab. 1 Dimension that significant contribute to role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue, emotional well-being.

6. Discussion

In this study, we investigated the contribution of interoceptive dimensions, multisensory processing, and body representation to daily functioning in active aging. Our study had two primary aims: first, to investigate whether early changes in interoception, affecting bodily processes, could reliably predict declines in daily functioning; and second, to develop and validate a battery of selected tests assessing specific aspects of interacting dimensions, including interoceptive dimensions, multisensory processes, and exteroceptive body representations. The tests included in the battery were selected based on their accuracy in predicting changes in daily life functioning in healthy elderly populations. We used a machine learning approach, Partial Least Squares Regression (PLSR), that offers a robust approach to examining the relationships between multiple predictors and outcomes. This method allowed us to integrate several bodily dimensions and explore how these dimensions interact to predict aspects of daily functioning in two steps: first, by focusing on interoceptive bodily dimensions, including interoceptive accuracy, sensibility, and awareness; and second, by integrating aspects of interoception with multisensory processes, and exteroceptive body representations such as body image, spatial tactile acuity, body structural representation, multisensory integration, multisensory temporal resolution, peripersonal space, temporal tactile acuity and sensorimotor functions, to understand how their interaction impacts active aging. This approach not only highlights the predictive power of interoceptive and exteroceptive measures but also offers a foundation for developing timely, user-centred interventions tailored to the needs and characteristics of older adults, with the purpose of slowing down the initial stages of physical decline and promoting healthier aging.

6.1 Predictive role of interoceptive dimensions to daily functioning

The first step of our analysis aimed to explore the predictive role of interoceptive bodily dimension to daily functioning. To this purpose, the analysis focused on the interoceptive dimensions, including interoceptive accuracy, interoceptive sensibility and interoceptive awareness, assessed through the battery of tests. These measures were selected based on their relevance to bodily awareness and their ability to capture age-related changes in interoceptive processing. Our findings show that different aspects of interoceptive sensibility, as assessed by specific subscales of the Multidimensional Assessment of Interoceptive Awareness (MAIA) and the Body Perception Questionnaire (BPQ), significantly predict specific aspects of daily functioning, including role limitations due to physical health problems, role limitation due to personal or emotional problems, energy/fatigue and emotional well-being. These results are consistent with prior studies that highlighted the importance of interoceptive sensibility in maintaining functional capacity and emotional regulation in aging populations (Carstensen et al., 2011; Kunzmann et al., 2000; Pfeifer & Cawkwell, 2025). For instance, individuals with higher interoceptive abilities tend to show greater emotional reactivity (Pfeifer & Cawkwell, 2025; Pollatos et al., 2007) and regulation (Füstös et al., 2013; Price & Hooven, 2018). However, aging is often related to reduced emotional reactivity (MacCormack et al., 2023), which may reflect a weakening of the mind-body connection observed in older adults (Mendes, 2010). Specifically, age-related changes in interoceptive dimensions have been shown to influence emotional experiences, with older adults often exhibiting reduced reactivity to high-arousal emotion, such as anger or fear, and an increased focus on positive, low-arousal emotions (MacCormack et al., 2021). This shift aligns with the Socioemotional Selectivity Theory (SST), which posits that older adults prioritize emotionally meaningful experiences as they perceive their time as limited (Carstensen et al., 1999). However, the underlying mechanisms of this emotional shift may also be linked to the weakening of mind-body connections observed in aging, where interoceptive signals become less integrated with emotional and cognitive processes (MacCormack et al., 2021; Mendes, 2010).

Self-Regulation (6M), which refers to ability to regulate distress by attending to bodily sensations, emerged as a significant predictor of role limitations due to physical health problems, that measure how physical health issues interfere with daily activities. This suggests that the ability to regulate distress through attention to bodily sensations is related to the perception of physical limitation and may help older adults better manage physical discomfort, potentially reducing limitations in daily activities. These findings align with research showing that interoceptive sensibility supports adaptive responses to physical activities (Wallman-Jones et al., 2021). The ability to self-regulate through bodily awareness may enable individuals to improve in physical tasks more effectively (Wallman-

Jones et al., 2021), even in the face of the natural physical changes associated with aging (Pfeifer & Cawkwell, 2025).

Similarly, for role limitations due to personal or emotional problems, that evaluate how emotional or psychological difficulties impact daily functioning, the Self-Regulation (6M), and Trusting (8M), that refers to the perception of the body as safe and trustworthy played a significant role. Additionally, BPQ-SUP that corresponding to the supradiaphragmatic reactivity scale and refers to the awareness of bodily states related to the functions of organs situated above the diaphragm, such as the heart and lungs, also contributed to predicting limitations in daily activities due to emotional problems. These aspects of interoceptive sensibility are involved in emotional wellbeing and emotional regulation (Carstensen et al., 2011; Kunzmann et al., 2000). The perception of the body as safe may contribute to emotional stability (Tamietto et al., 2018) reducing the impact of emotional distress on daily functioning.

Importantly, these findings are in line with embodied cognition models of aging (Pfeifer & Cawkwell, 2025), which propose that physiological changes and sensory decline disrupt the integration of exteroceptive and interoceptive sensations, impacting body representation and the sense of self (Costello & Bloesch, 2017; Kuehn et al., 2018). While age-related declines in interoceptive accuracy may weaken this integration (Monti et al., 2021), the ability to trust one's body and regulate emotions through bodily awareness may serve as a compensatory mechanism, helping older adults maintain emotional resilience.

Energy/fatigue, that refers to the perceived levels of vitality and fatigue, is predicted by heart rate frequency (mean HR) and different aspects of interoceptive sensibility, including the Not-Distracting scale (2M) that refers to the ability to not distract oneself from sensation of pain or discomfort, the Trusting scale (M8), the Supradiaphragmatic reactivity scale (BPQ-SUP) and the body awareness and the subdiaphragmatic reactivity scale (BPQ-BOA/SUB). Fatigue has a measurable relationship with cardiac functioning (Nelesen et al., 2008). Specifically, research has shown that heart rate (HR) is a key indicator of physical effort and energy expenditure, with higher HR often associated with increased perceived fatigue (Nelesen et al., 2008). This suggests that HR may serve as a physiological marker of fatigue, particularly in contexts where individuals experience prolonged or intense physical demands. Previous research shows that heart rate plays a role in maintaining energy levels and reducing fatigue and heart rate variability (HRV) is linked to energy balance and fatigue (Thayer et al., 2012). Specifically, resting cardiac autonomic balance, characterized by parasympathetic dominance over sympathetic influences, favours energy conservation and recovery. Recent studies have further emphasized the role of cognitive fatigue in influencing physical performance,

highlighting that fatigue is a brain-derived emotion that regulates exercise behaviour to ensure the protection of whole-body homeostasis (Marcora et al., 2009). This perspective aligns with our findings, suggesting that interoceptive sensibility may play a key role in modulating the perception of fatigue by integrating bodily signals with cognitive and emotional processes (McMorris, 2020). In more details, the ability to attend to and trust bodily sensations (as measured by the Trusting scale) may help individuals better manage cognitive fatigue, thereby maintaining energy levels and physical performance even in the face of physiological challenges. Additionally, the Not-Distracting scale may reflect a capacity to tolerate discomfort, which could be crucial for sustaining effort during physically demanding tasks. This suggests that both physiological markers, including heart rate and subjective interoceptive sensibility contribute to the perception of energy and fatigue levels and their regulation in daily life; particularly, these findings underscore the importance of interoceptive sensibility in regulating both cognitive and physical aspects of fatigue.

For emotional well-being, which assesses feelings of happiness, anxiety, and depression, providing insight into overall emotional health, interoceptive sensibility, as measured by the Self-Regulation (6M), and Trusting (8M) scales, and the Supradiaphragmatic reactivity scale (BPQ-SUP) were significant predictors, confirming the previous results on role limitations due to personal or emotional problems, highlighting the link between interoception and emotional regulation (Barrett, 2017; Feldman et al., 2024). The integration of interoceptive signals with emotional processes is crucial for maintaining emotional well-being. Research suggests that interoceptive sensibility enhances emotional regulation by allowing individuals to accurately interpret and respond to bodily signals associated with emotional states (Füstös et al., 2013; Price & Hooven, 2018). In older adults, this integration may be particularly important, as age-related declines in interoceptive accuracy can disrupt the connection between bodily sensations and emotional experiences (MacCormack et al., 2023; Mendes, 2010). However, the ability to trust one's body and regulate emotions through bodily awareness may help compensate for these declines, promoting emotional resilience and well-being. These findings also align with embodied cognition models, which emphasize the role of interoceptive signals in shaping emotional experiences and maintaining a coherent sense of self (Costello & Bloesch, 2017; Kuehn et al., 2018).

In summary, our findings on the first step highlight that interoceptive sensibility, as measured by specific subscales of the MAIA and BPQ, plays a crucial role in predicting various aspects of daily functioning in older adults. The Not-Distracting scale (2M), which reflects the ability to not distract oneself from sensations of pain or discomfort, was a significant predictor of energy/fatigue. The Self-Regulation scale (6M), which reflects the ability to regulate distress by attending to bodily sensations,

emerged as a significant predictor of role limitations due to physical health problems, role limitations due to personal or emotional problems, and emotional well-being. The Trusting scale (8M), which measures the perception of the body as safe and trustworthy, was a significant predictor of role limitations due to personal or emotional problems, energy/fatigue, and emotional well-being. The Supradiaphragmatic reactivity scale (BPQ-SUP), which measures awareness of bodily states related to organs above the diaphragm, contributed to predicting role limitations due to emotional problems and energy/fatigue. Additionally, the Body Awareness and Subdiaphragmatic reactivity scale (BPQ-BOA/SUB), which captures awareness of bodily states related to organs below the diaphragm, was a significant predictor of energy/fatigue and emotional well-being. Finally, heart rate (HR), as a physiological measure, was a significant predictor of energy/fatigue.

Interestingly, interoceptive accuracy and awareness did not emerge as significant predictors in this step, which contrasts with some previous studies that have emphasized the role of objective interoceptive abilities in aging (Khalsa et al., 2009; Murphy et al., 2018). This discrepancy may be since interoceptive sensibility, as a subjective measure, captures a broader range of bodily experiences that are more directly relevant to daily functioning. Alternatively, it may reflect the complexity of interoceptive processing in aging, where subjective perceptions of bodily states may become more salient than objective accuracy. Importantly, our study focuses on different aspects assessed by SF-36 Health Survey (e.g., role limitations, energy/fatigue, emotional well-being) rather than directly examining age-related changes. This approach allows us to identify which aspects of interoception contribute to specific dimensions of daily functioning, instead of focusing on how interoception declines with age. This distinction may explain why subjective measures of interoception, such as the MAIA and BPQ subscales, were more predictive than objective measures like interoceptive accuracy.

Finally, the subjective interoceptive sensibility may compensate for well-documented age-related declines in objective interoceptive accuracy (Khalsa et al., 2009); this could explain why interoceptive accuracy did not emerge as a significant predictor in our study. The reliance on subjective interoceptive sensibility may, therefore, allow older adults to maintain functional capacity despite physiological changes.

6.2 Predictive role of interaction between interoceptive and exteroceptive bodily dimensions to daily functioning

The second step of our analysis aimed to explore whether and how the inclusion of exteroceptive bodily dimensions interact with interoceptive bodily dimensions to predict daily functioning

outcomes for the SF-36 scales that were significantly predicted by interoceptive measures in the previous step. To this purpose, we included in the analysis the exteroceptive dimensions assessed through the battery of tests. The exteroceptive dimensions included were body image, spatial tactile acuity, body structural representation, multisensory integration, multisensory temporal resolution, peripersonal space, temporal tactile acuity and sensorimotor functions. These measures, assessed through the battery, were selected based on their relevance to bodily awareness and their ability to capture age-related changes in interoceptive processing.

Specifically, we focused on role limitations due to physical health problems, role limitations due to personal or emotional problems, energy/fatigue, and emotional well-being. Our findings reveal that the addition of exteroceptive bodily dimensions, such as body image, spatial tactile acuity, peripersonal space and sensorimotor functions, enhanced the predictive power of our models for role limitations due to physical health problems, energy/fatigue, and emotional well-being providing evidence of an interaction between interoceptive and exteroceptive bodily dimension in active aging.

However, interoceptive dimensions were sufficient to predict outcomes for role limitations due to personal or emotional problems, suggesting that aspects of interoceptive sensibility, as measured by MAIA and BPQ, play a central role in this aspect of daily functioning.

Body image significantly contribute to the role limitations due to physical health problems and emotional well-being. These findings suggest that the way individuals perceive their bodies, particularly any discrepancies between their actual and ideal body, is closely involved in the perception of physical capacities(Alleva & Tylka, 2021) and emotional state(Wilson et al., 2013). In line with this findings, previous research shows that appreciating body functionality, such as valuing physical abilities, is linked to a more positive body image(Bailey et al., 2015; Frisén & Holmqvist, 2010; Gattario & Frisén, 2019). Additionally, physical capacities appreciation is associated with interoceptive sensibility further supporting its role in shaping how individuals perceive their physical capacities(Todd et al., 2019). Moreover, body image plays a critical role in psychological well-being, influencing emotional regulation and self-esteem(Wilson et al., 2013); positive body image is associated with greater engagement in physical activities and better adherence to health-promoting behaviours. This is consistent with our findings showing that both physical and emotional aspects of daily functioning were predicted by body image and interoceptive sensibility.

For role limitations due to personal or emotional problems, however, the addition of body representation variables did not change the predictive power of the model identified in the first step. This suggests that interoceptive sensibility, particularly the ability to self-regulate and the perception of the body as safe and trustworthy, remains the primary predictor of limitation due to emotional

problems in daily functioning. This finding can be explained by considering the focus of this scale, which measures how emotional difficulties interfere with daily activities. The ability to self-regulate distress through attention to bodily sensations (Self-Regulation) and the perception of the body as safe (Trusting) may allow individuals to cope with emotional challenges effectively, preventing them from disrupting daily activities. In contrast, emotional well-being, which reflects a broader and general state of emotional health, is influenced by both interoceptive and exteroceptive bodily dimensions, as it encompasses not only emotional regulation but also factors such as body image that together may influence self-perception.

Regarding the energy/fatigue model, most predictors were confirmed as significant. Heart rate (mean HR) and interoceptive sensibility, specifically the ability to perceive bodily states related to supradiaphragmatic (BPQ-SUP), the body awareness and the subdiaphragmatic (BPQ-BOA/SUB), were confirmed as a key predictor of energy and fatigue levels. Additionally, peripersonal space (PSE-pps), spatial tactile acuity (C-arm), and sensorimotor function (SC) further improved the predictive power of the model.

Peripersonal space significantly contribute to energy/fatigue. This space is dynamically shaped by multisensory integration, combining visual, tactile, and proprioceptive inputs, and is crucial for planning and executing movements efficiently. Research comparing healthy young and older adults has shown that ageing significantly affects the representation of peripersonal space and body schema (Sorrentino et al., 2021), with consequence of reduced efficiency in multisensory integration. This decline in multisensory processing can result in less accurate spatial orientation and motor coordination, making everyday tasks more demanding for older adults. Peripersonal space allows individuals to interact with objects and navigate their surroundings more efficiently (di Pellegrino & Làdavas, 2015; Serino, 2019b). For older adults, a reduced peripersonal space could lead to increased cognitive and physical effort when performing daily tasks, such as reaching for objects or avoiding obstacles (Chepishcheva, 2023; Ruggiero et al., 2017). This effort can contribute to a faster depletion of energy reserves, leading to higher levels of fatigue (Mahoney, Cotton, Verghese, et al., 2019).

Additionally, spatial tactile acuity contributes to energy/fatigue. Spatial tactile acuity reflects the ability to perceive and discriminate fine spatial details through touch, which is essential for efficient movement and energy conservation and tends to decline with aging (McIntyre et al., 2021; Stevens & Cruz, 1996). When tactile perception is impaired, individuals may require more cognitive and physical effort to perform tasks (Löffler et al., 2024), such as reaching for objects or avoiding obstacles. This increased effort may lead to higher energy expenditure and greater fatigue. Moreover,

a recent study demonstrated that muscle fatigue significantly increases the two-point discrimination distance (Han et al., 2015) indicating a reduction in tactile acuity.

The sum of confusion is linked to the cognitive effort required to resolve conflicting sensory information. When hands are crossed, the brain must work harder to remap tactile sensations (J. C. Craig et al., 2010; Ferri et al., 2016; Yamamoto & Kitazawa, 2001), which can be mentally taxing. This increased cognitive load can contribute to feelings of fatigue, especially in older adults who may already have reduced cognitive reserves.

Overall, our findings from the second step highlight the importance of integrating body representation measures with interoceptive dimensions to better understand daily functioning in active aging. By including exteroceptive variables, we found that body image, peripersonal space, spatial tactile acuity and sensorimotor function, in interaction with interoceptive sensibility, contribute to predicting specific aspects of daily functioning, such as role limitations due to physical health problems, energy/fatigue (also predicted by mean HR), and emotional well-being. These results provide a more comprehensive model of how bodily awareness and bodily processing contribute to functional capacity and emotional well-being in older adults.

One of the key contributions of this study is the development of a comprehensive test battery that integrates interoceptive, exteroceptive, and multisensory measures to predict daily functioning in older adults. This battery represents a significant advancement over traditional cognitive assessments, which often ignore the role of bodily awareness in aging. The results of this study suggest that such a battery could be a valuable tool for early identification of decline in daily functioning, allowing for timely, user-centred interventions tailored to the specific needs of older adults. For instance, interventions could focus on enhancing interoceptive awareness through mindfulness-based practices or biofeedback training (Chelidoni et al., 2020; Economides et al., 2020), which have been shown to improve emotional regulation and physical functioning in older populations. Additionally, the inclusion of exteroceptive measures, opens the door to innovative rehabilitation programs that target multisensory integration and motor coordination, potentially reducing the risk of falls and improving overall mobility (Mahoney, Cotton, Verghese, et al., 2019). As a next step, future research should aim to validate this battery in larger, more diverse populations, including individuals with chronic health conditions or lower educational attainment, to ensure its broader applicability and effectiveness. Additionally, further development could explore the potential for digital adaptation of the battery, enabling remote monitoring and personalized interventions to support active aging.

Despite the significant findings, this study has several limitations that need to be acknowledged. First, although the sample covered a wide age range, it primarily consisted of healthy individuals with a

relatively high level of education. This may limit the generalizability of the results to populations with chronic health conditions or lower educational attainment. Additionally, the study's design does not allow for the establishment of causal relationships between interoceptive dimensions, body representation, and daily functioning; future studies could investigate how these factors evolve and influence one another across different stages of aging. Another limitation is the reliance on self-reported measures to assess interoceptive sensibility and daily functioning, which may be subject to response bias. Although these measures are widely used and validated, future research could integrate additional objective measures to complement self-reports. Furthermore, this study focused primarily on cardiac interoception. While cardiac interoception is a well-established and widely used metric, it represents only one aspect of interoceptive processing. Expanding the range of interoceptive dimensions (e.g. respiratory, gastric, or thermoregulatory signals) could provide a more comprehensive understanding of how interoception influences daily functioning in older adults.

In conclusion, this study provides significant evidence for the role of interoceptive dimensions and body representation in predicting daily functioning in older adults. Building on previous literature, we have developed a comprehensive battery of tests that integrates interoceptive, exteroceptive, and multisensory measures, offering a practical tool for early identification of declines in functional capacity. This battery not only enhances our understanding of the factors influencing daily functioning but also opens the door for targeted interventions aimed at promoting active aging and improving quality of life. These findings may have practical implications for the development of interventions aimed at improving bodily awareness in older adults, with the goal of promoting healthy and active aging and improve the quality of life in older adults.

CHAPTER 5.

Impact of interoception and multisensory integration on functional and physical activities in aging

1. Introduction

According to Eurostat and North American statistics on functional and activity limitations, approximately half of the elderly population (aged 65 years and older) reports experiencing difficulties with daily activities (Elgaddal & Kramarow, 2022). This highlights the profound impact of aging on physical and functional abilities, which often manifest as perceived restrictions in performing specific actions such as walking, climbing stairs, or lifting objects (Verbrugge & Jette, 1994). These functional limitations are not solely due to physical decline but are also shaped by age-related changes in sensory processing.

As individuals age, there is an unnoticed but significant increase in sensory thresholds across various modalities, including vision, hearing, smell, touch, temperature sensation, and pain perception. This means that stronger and more pronounced stimuli are required for sensory information to be consciously perceived. Such sensory changes impair the brain's ability to acquire, process, and integrate information from the body and the environment, creating significant challenges for movement autonomy and the performance of daily activities (Gescheider et al., 1994; Gibson & Farrell, 2004). For instance, difficulties in detecting and interpreting sensory cues can reduce an individual's ability to navigate their surroundings safely and effectively.

The reliability of sensory signals plays a crucial role in multisensory integration, particularly in defining the time interval within which stimuli from different sensory modalities are perceived as simultaneous or causally connected, also known as the *temporal binding window* (McGovern et al., 2022). In older adults, the ability to select and integrate sensory signals diminishes, leading to less precise and more variable sensory processing. This reduced sensory reliability results in a broader temporal binding window, which can negatively impact coordination and perception (Basharat et al., 2019; Brooks et al., 2018; Cao et al., 2019). Research shows that older adults with a wider temporal binding window are more likely to experience falls, suggesting a direct link between multisensory integration and physical stability (Mahoney, Cotton, Verghese, et al., 2019; McGovern et al., 2022; Setti et al., 2011).

Multisensory integration is also closely tied to motor skills and body awareness. Effective coordination of sensory inputs is essential for guiding everyday actions, from maintaining balance to executing precise movements. When sensory integration falters, the awareness of bodily states can become compromised, leading to impaired movement autonomy and difficulties in performing daily

activities. These findings underscore the importance of multisensory processing and body awareness in maintaining functional independence in older adults. Recognizing this connection could inform interventions aimed at enhancing sensory reliability and improving quality of life for the aging population.

Bodily awareness, however, relies not only on proprioceptive and exteroceptive senses—those that detect stimuli originating from outside the body—but also on *interoception*, which refers to sensations arising from within the body, such as the heartbeat, breathing, hunger, and thirst (Cameron, 2001; A. D. Craig, 2002; Critchley et al., 2004; A. Damasio, 2003; Khalsa et al., 2009; Mayer et al., 2006; Vaitl, 1996). Interestingly, aging has been linked to a decline in interoceptive accuracy and awareness (Khalsa et al., 2009; Murphy et al., 2018) and alterations in interoceptive brain networks (Dobrushina et al., 2020), highlighting significant changes in how the brain processes internal bodily signals.

Together, these changes in sensory and multisensory perception, as well as in interoceptive processing and awareness, likely impact daily life by influencing an individual's ability to recognize and respond to internal needs, as well as to plan and execute actions to meet those needs.

However, in aging the relationship between interoception, multisensory integration, and their impact on daily functional and physical activities remains largely underexplored.

1.1 Overview of the study

This study aimed to investigate whether, and how, the quality of physical functioning in daily activities among healthy elderly individuals, compared to a younger cohort, could be predicted by temporal sensitivity in multisensory perception as well as interoceptive processing and awareness. To explore this, both young and elderly participants completed the Short Form Health Survey 36 questionnaire (SF-36) (Apolone & Mosconi, 1998) which includes eight subscales that assess various aspects of health-related quality of life, ranging from physical functioning to social and emotional well-being.

In addition, we assessed various interoceptive dimensions in the participants. According to Garfinkel et al. (2015), interoception can be divided into three distinct components: interoceptive accuracy, which refers to the objective ability to detect internal bodily sensations; interoceptive sensibility, which reflects the subjective evaluation or confidence in recognizing these internal bodily sensations; and interoceptive awareness, which pertains to metacognitive awareness of one's interoceptive abilities. To evaluate these dimensions, participants completed the Heartbeat Counting Task (commonly known as the Schandry Task; R. Schandry, 1981) and the Heartbeat Detection Task (also referred to as the Tapping or Tracking Task; Brener & Ring, 2016; McFarland RA., 1975). The Schandry Task primarily focuses on the perception of internal bodily signals, whereas the Tapping

Task is designed to assess sensory and motor integration. Previous studies have demonstrated age-related declines in interoceptive functioning using these tasks (Dobrushina et al., 2020; Herbert et al., 2018). Additionally, participants completed the Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire (Calì et al., 2015; Mehling et al., 2012), a validated tool for assessing the interoceptive sensibility component across various age groups.

Finally, to assess temporal sensitivity in multisensory perception, we employed two tasks widely used in the literature: the audio-tactile Simultaneity Judgment task (SJ) and the Temporal Order Judgment task (TOJ) with both crossed and uncrossed hands (Basharat et al., 2018; Kostaki M. & Vatakis A., 2018). The SJ task evaluates the ability to determine whether stimuli from different sensory modalities (auditory and tactile) occur simultaneously or at different times (Keetels & Vroomen, 2012). The TOJ task, on the other hand, serves two distinct purposes: with uncrossed hands, it provides a baseline measure of the temporal resolution of the somatosensory system (Sternberg & Knoll, 1973) while with crossed hands, it assesses the multisensory representation of body space, particularly the sensory integration process between tactile signals and visuo-proprioceptive cues. Although involving different sensory modalities, both SJ and TOJ tasks have been successfully employed in studies with older adults, revealing a reduction in temporal sensitivity when distinguishing whether sensory stimuli occur simultaneously or sequentially (Basharat et al., 2018). Importantly, the SJ and TOJ tasks do not require rapid motor responses, enabling a more accurate assessment of how perceptual processing evolves with age. This approach avoids the potential confound of motor-response speed, which can obscure the distinction between age-related changes in perceptual abilities and those in motor functions, as occurs in reaction time tests.

We hypothesized that age-related declines in both multisensory perception and interoceptive processing and awareness could negatively influence the physical aspects of health-related quality of life. This effect may arise from changes in an individual's interoceptive representation of bodily needs and their multisensory representation of body space. In other words, since both interoception and multisensory integration deteriorate with age, we propose that these declines may serve as predictors of physical functioning in older adults.

2. Methods and materials

2.1 Participant

Twenty-one young (10 female; aged 21–38, mean = 29, SD = 5.52), twenty-three old adults (18 female; aged 58–87, mean = 68, SD = 6.78), participated in the study after providing written informed

consent. The younger adults were recruited through an online questionnaire. Older adults were recruited at UniTre Associazione Nazionale delle Università della Terza Età (National Association of Universities of the Third Age) – Chieti (Italy). The mini-mental state examination was used to evaluate the participants' cognitive function (Folstein et al., 1975; Grigoletto et al., 1999; Magni et al., 1996). Individuals who had a mini-mental state examination score that was lower than 26 were excluded. No participant had a history of neurologic, general medical or psychiatric conditions and/or medical conditions that could potentially affect cognitive functioning (e.g., Alzheimer's disease, multiple sclerosis, and Parkinson's disease). The experimental protocol was approved by the Institutional Ethics Committee at the University G. d'Annunzio, Chieti-Pescara. The sensitivity analysis (Perugini et al., 2018) showed that with a power = 0.80, $\alpha = .05$, and 23 participants, our test could reliably detect an effect size (Cohen's f) of at least 1.71, corresponding to a R^2 of .74.

2.2 Experimental procedure

Participants completed the SF-36 questionnaire (Apolone & Mosconi, 1998) to evaluate physical functioning, as well as tasks assessing multisensory integration and interoception. While originally developed for adult populations, the SF-36 has been validated in younger cohorts, including adolescents and young adults, in various studies. Its robust psychometric properties make it suitable for evaluating health-related quality of life across age groups, providing reliable and comparable data on physical functioning, even in youth. To complement this assessment, multisensory integration was evaluated using the Simultaneity Judgment (SJ) and Temporal-Order Judgment (TOJ) tasks. Interoception was assessed through three established measures: the Heartbeat Counting task (R. Schandry, 1981), the Heartbeat Detection task (Brener & Ring, 2016; McFarland, 1975), and the Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire (Mehling et al., 2012). The experiment lasts about 1h 30 min (Figure 1).

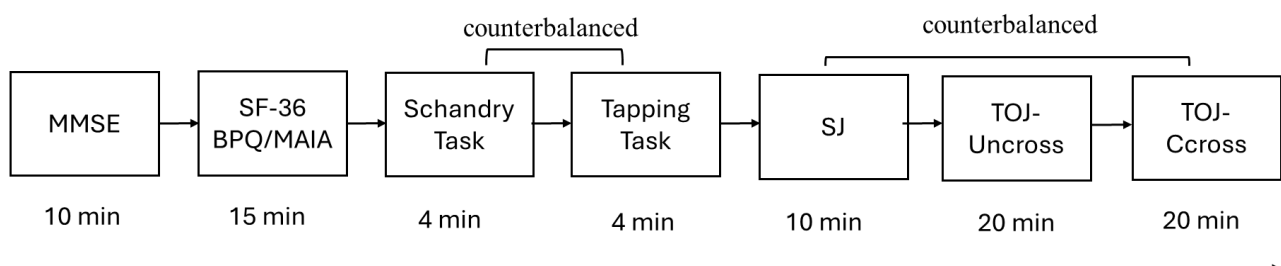


Figure 1. Example of experimental flow of the procedure.

2.3 Multisensory Integration Tasks

Simultaneity Judgment (SJ)

Simultaneity Judgment (SJ) task was employed to evaluate Multisensory Temporal Resolution that refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. SJ aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Auditory stimuli were delivered through headphones and consisted of a 3,500-Hz pure tone lasting 30ms. Tactile stimuli were administered using two constant-current electrical stimulators (Digitimer DS7A), which controlled two pairs of neurological electrodes attached to the participant's right and left middle fingers. Tactile stimuli were single, constant voltage, rectangular monophasic pulses lasting 100 μ s. During the task, participants were blindfolded and comfortably seated at a table, with their index fingers resting on separate keys of a response box. The intensity of the stimuli was adjusted to each participant's detection threshold, set at 100% for both auditory and tactile stimuli. In each trial, two stimuli were presented in opposite hemispaces, with stimulus pairs randomly interleaved at various stimulus onset asynchronies (SOAs): ± 450 , ± 350 , ± 200 , ± 120 , ± 70 , ± 40 , ± 15 , and 0 ms. Participants had to indicate whether the two stimuli were presented simultaneously or not using the response box. The AT-SJ task comprised two blocks, each consisting of 120 trials, resulting in a total of 240 trials (16 trials per SOA). The association between the side of presentation (right or left) and the modality (auditory or tactile) was balanced across trials, and the stimulus-response association was counterbalanced between blocks.

Temporal-Order Judgment task (TOJ, uncrossed hands)

Temporal Order Judgment (TOJ) task was employed to evaluate Temporal Tactile Acuity that refers to the ability to perceive and discriminate temporal aspects of tactile stimuli.

During TOJ, participants were blindfolded and seated at a table with their hands placed palm down on the table surface. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli, (i.e., stimulus onset asynchrony SOA), was randomly assigned from 22 intervals. In the uncrossed condition, it ranged from -450 to 450 ms (± 450 , ± 300 , ± 200 , ± 150 , ± 100 , ± 75 , ± 50 , ± 40 , ± 30 , ± 15 , ± 5 ms). Negative and positive intervals indicated whether the left or right hand was stimulated first. The inter-trial intervals varied between 2000 and 4000 ms. Each condition comprised 176 trials, with 8 trials per SOA¹⁹. Tactile stimuli were delivered using two constant-current electrical stimulators (Digitimer DS7A), which controlled pairs of neurological electrodes attached to the dorsal surface of the middle fingers. The

stimuli were supra-threshold vibrotactile stimuli oscillating at 100 Hz, with a total duration of 30ms. They were instructed to make two-alternative forced-choice judgments regarding the order of stimulation by pressing the button under the index finger of the hand they believed was stimulated earlier or later than the other. The two response strategies (earlier and later) were counterbalanced. Trials with response times exceeding 3000 ms or without a response were re-presented at the end of the corresponding block, ensuring an equal number of trials across all experimental conditions. No feedback was provided to the participants.

Temporal-Order Judgment task (TOJ, crossed hands)

To perceive the location of touch in space, the brain combines information about touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands (Azañón et al., 2016). This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (Ferri et al., 2016).

In crossed condition, participants were instructed to cross their arms over their wrists. The two possible arm positions (right over left and vice versa) were counterbalanced across participants, and the order was randomly assigned to each participant. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli ranged from -900 to 900 ms (± 900 , ± 600 , ± 400 , ± 300 , ± 200 , ± 150 , ± 100 , ± 80 , ± 60 , ± 30 , ± 10 ms).

2.4 Interoceptive Tasks

Heartbeat Detection task

Heartbeat Detection task, also known as the Tapping or Tracking task (Brener & Ring, 2016; McFarland, 1975) is used to assess participants' ability to accurately perceive and count their own heartbeats. It was employed to measure the interoceptive dimensions (i.e. Interoceptive accuracy, sensibility and awareness). During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. The task consisted of two time periods, each lasting 2 minutes, with a pause between them. Following each time interval, participants were required to verbally report their level of confidence in their perceived accuracy of heartbeat detection.

This confidence rating was recorded using a scale from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

Heartbeat Counting Task

The Heartbeat Counting task (R. Schandry, 1981), or Schandry task, is used to assess participants' ability to accurately perceive and count their own heartbeats. This task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and count the number of heartbeats they feel. The task consists of four different time periods: 25 seconds, 30 seconds, 45 seconds, and 100 seconds (Pollatos et al., 2008). These time periods are presented in a random order to avoid predictable patterns. During each time interval, participants were instructed to focus their attention on their heart activity and bodily sensations. They were specifically asked to count and keep track of their felt heartbeats without engaging in any physical manipulations, such as taking their pulse or using external cues. Participants were also discouraged from using the duration of the time interval as a basis for estimating the number of heartbeats. The task begins with a 10-second introductory phase to allow participants to settle into the task. Each period is presented separately, with a pause between each trial. Following each time interval, participants were required to verbally report the counted number of heartbeats they perceived. These responses were manually recorded by the experimenter for later analysis. At the end of each trial, participants were immediately asked to indicate their level of confidence (Garfinkel et al., 2015; Khalsa et al., 2018) regarding the accuracy of their responses on a scale ranging from 1 “Total guess/No heartbeat awareness” to 9 “Complete confidence/Full perception of heartbeat”. The evaluation of confidence levels was manually conducted by recording the participants' responses.

Multidimensional Assessment of Interoceptive Awareness (MAIA)

The MAIA (Mehling et al., 2012) is composed of 32 items on a 6-points Likert scale, in which the participant must rate “how often each statement applies to you generally in daily life,” with ordinal responses coded from 0 (“never”) to 5 (“always”). This multidimensional instrument measures Interoceptive sensibility on eight scales: (1) Noticing, the awareness of one's body sensations; (2) Not-distracting, the tendency not to ignore or distract oneself from sensations of pain or discomfort; (3) Not-worrying, the tendency not to experience emotional distress or worry with sensations of pain

or discomfort; (4) Attention regulation, the ability to sustain and control attention to body sensation; (5) Emotional awareness, the awareness of the connection between body sensations and emotional states; (6) Self-regulation, the ability to regulate psychological distress by attention to body sensations; (7) Body listening, the tendency to actively listen to the body for insight; and (8) Trusting: the experience of one's body as safe and trustworthy.

3. Data analysis

Simultaneity Judgment (SJ)

We calculated two parameters from SJ: the point of subjective equality (PSE), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the 'just noticeable difference' (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed (Binder, 2015). The analysis of participants' responses allowed us to measure temporal sensitivity in the integration of multisensory stimuli. The response data were analysed using a Gaussian distribution to calculate the point of subjective equality (PSE-sj) ranged from -13.37 to 16.21 (mean $\pm$ SD: 2.03 ± 8.09) for young people and ranged from -343.97 to 191.64 (mean $\pm$ SD: -7.59 ± 96.87) for elderly people; and the just noticeable difference (JND-sj) ranged from 60.43 to 190.83 (mean $\pm$ SD: 112.83 ± 32.85) for young people, and ranged from 119.26 to 1493.05 (mean $\pm$ SD: 301.75 ± 333.10) for elderly people.

Temporal-Order Judgment task (TOJ – uncrossed/cross hands)

From TOJ, we measured both the JND for uncrossed and cross condition (JND-toju; JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first (Kostaki & Vatakis, 2018) and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions.

The mean response times (RT) and participant responses were calculated by considering the temporal distance between stimuli (SOA). To analyse the experimental data, a fitting function was applied using a normal distribution model; we quantified the JND for the uncrossed condition (JND-toju) ranged from 19.64 to 111.21 (mean $\pm$ SD: 56.30 ± 29.50) for young people and ranged from 16.64 to 246.96 (mean $\pm$ SD: 96.04 ± 55.47) for elderly people. Using the same fitting function, we quantified

the JND for the crossed condition (JND-tojc) ranged from 16.88 to 190.03 (mean $\pm$ SD: 66.43 ± 40.41) for young people and ranged from 21.36 to 500.01 (mean $\pm$ SD: 133.06 ± 111.19) for elderly people. This modelling approach aimed to find the best-fitting parameters that described the observed data patterns (Yamamoto & Kitazawa, 2001).

To quantify the overall difference between the 'Cross' and 'Uncross' conditions, the cumulative sum of differences between the fitted models was computed. This yielded a global indicator of difference, denoted as SC, ranged from 0.00 to 470.15 (mean $\pm$ SD: 76.40 ± 95.77) for young people and ranged from -10.60 to 500.92 (mean $\pm$ SD: 113.25 ± 126.88) for elderly people, which provided an overarching measure of the divergence between the two conditions (Wada et al., 2014).

Heartbeat Detection task

To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). The analysis involves categorizing the tapping responses based on the participant's heart rate (HR) (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). Three categories are used: $HR < 69.75$, $69.75 < HR < 94.25$, and $HR > 94.25$. For each recorded heartbeat, the difference between the tapping time and the nearest R-peak is calculated. If the HR falls into one of the predefined categories, the tapping response within a specific time window is considered correct. The number of correct tapping responses is tallied for each HR category. The total correct responses for $HR < 69.75$, $69.75 < HR < 94.25$, and $HR > 94.25$ are denoted as corr_69, corr_betw, and corr_94, respectively. The task accuracy is then calculated as follows: $\text{accuracy} = 1 - (|\text{recorded_heartbeats} - (\text{corr_69} + \text{corr_betw} + \text{corr_94})| / \text{recorded_heartbeats})$ (Zaccaro et al., 2022). The accuracy (Acc-d) ranged from 0.40 to 0.99 (mean $\pm$ SD: 0.77 ± 0.16) for young people and ranged from 0.20 to 0.94 (mean $\pm$ SD: 0.68 ± 0.20) for elderly people.

We evaluated the sensibility through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat). The confidence (Con-d) ranged from 2.00 to 8.25 (mean $\pm$ SD: 5.06 ± 1.71) for young people and ranged from 1.50 to 8.50 (mean $\pm$ SD: 5.83 ± 1.90) for elderly people.

The awareness was calculated comparing the accuracy and the confidence through the absolute difference between the rescaled (min-max normalization) measures of interoceptive accuracy and

confidence (Mattioni et al., 2024); the awareness (Aw-d) ranged from 0.24 to 0.99 (mean $\pm$ SD: 0.72 ± 0.22) for young people and ranged from 0.20 to 0.99 (mean $\pm$ SD: 0.70 ± 0.25) for elderly people.

Heartbeat Counting Task

The Heartbeat Counting task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats (Koch et al., 2014). The participants' interoceptive accuracy score was computed according to the formula: $\text{Accuracy} = 1/4 \sum [1 - (|\text{recorded heartbeats} - \text{counted heartbeats}| / \text{recorded heartbeats})]$. The accuracy (Acc-c) ranged from 0.34 to 0.98 (mean $\pm$ SD: 0.75 ± 0.19) for young people and ranged from 0.22 to 0.98 (mean $\pm$ SD: 0.66 ± 0.21) for elderly people.

At the end of each trial, participants were immediately asked to indicate their level of confidence (also referred to as interoceptive “sensitivity”) (Garfinkel et al., 2015; Khalsa et al., 2018) regarding the accuracy of their responses on a scale ranging from 1 “Total guess/No heartbeat awareness” to 9 “Complete confidence/Full perception of heartbeat”. The confidence (Con-c) ranged from 4.50 to 9.00 (mean $\pm$ SD: 6.58 ± 1.23) for young people and ranged from 4.13 to 8.75 (mean $\pm$ SD: 6.98 ± 1.39) for elderly people.

The awareness was calculated comparing the accuracy and the confidence through the absolute difference between the rescaled (min-max normalization) measures of interoceptive accuracy and confidence (Mattioni et al., 2024); the awareness (Aw-c) ranged from 0.32 to 0.95 (mean $\pm$ SD: 0.70 ± 0.17) for young people and ranged from 0.02 to 0.98 (mean $\pm$ SD: 0.65 ± 0.21) for elderly people.

Multidimensional Assessment of Interoceptive Awareness (MAIA)

The MAIA generally evaluates multiple dimensions of interoceptive sensitivity. From the MAIA we obtained a score for each subscale: Noticing (1M), Not-Distracting (2M) Not-Worrying (3M) Attention Regulation (4M) Emotional Awareness (5M) Self-Regulation (6M) Body Listening (7M) Trusting (8M).

The score for each scale is calculated by averaging the scores of its individual items and thus can vary in the 0–5 range. The (1) Noticing scores ranged from 0.75 to 4.50 (mean $\pm$ SD: 3.21 ± 0.83) for young people and ranged from 0.50 to 5.00 (mean $\pm$ SD: 2.41 ± 1.35) for elderly people; (2) Not-

distracting scores ranged from 1.00 to 3.50 (mean $\pm$ SD: 2.29 ± 0.61) for young people and ranged from 0.00 to 3.67 (mean $\pm$ SD: 1.88 ± 0.96) for elderly people; (3) Not-worrying scores ranged from 0.33 to 4.33 (mean $\pm$ SD: 2.54 ± 1.09) for young people and ranged from 0.00 to 4.00 (mean $\pm$ SD: 2.39 ± 0.89) for elderly people); (4) Attention regulation scores ranged from 1.00 to 5.00 (mean $\pm$ SD: 3.09 ± 0.95) for young people and ranged from 0.57 to 5.00 (mean $\pm$ SD: 2.82 ± 1.10) for elderly people; (5) Emotional awareness scores ranged from 1.00 to 5.00 (mean $\pm$ SD: 3.52 ± 0.95) for young people and ranged from 0.00 to 5.00 (mean $\pm$ SD: 3.48 ± 1.09) for elderly people; (6) Self-regulation scores ranged from 0.50 to 5.00 (mean $\pm$ SD: 2.70 ± 1.16) for young people and ranged from 0.50 to 5.00 (mean $\pm$ SD: 2.98 ± 1.13) for elderly people); (7) Body listening scores ranged from 0.00 to 5.00 (mean $\pm$ SD: 2.78 ± 1.08) for young people and ranged from 0.00 to 5.00 (mean $\pm$ SD: 2.76 ± 1.51) for elderly people) and (8) Trusting scores ranged from 1.00 to 5.00 (mean $\pm$ SD: 3.25 ± 1.03) for young people and ranged from 1.00 to 5.00 (mean $\pm$ SD: 3.92 ± 1.24) for elderly people.

3.1 Statistical Analysis

Multiple regression analyses were conducted using a stepwise forward method to examine the relationships between physical health dimensions, interoceptive measures, and multisensory integration. The dependent variables included the dimensions of the SF-36 questionnaire related to the physical domain: Physical Functioning, Role Limitations Due to Physical Health, Energy/Fatigue, and General Health. The independent variables consisted of interoceptive measures (Aw-c, Aw-d, and the eight dimensions of the MAIA questionnaire) and multisensory integration measures (JND-sj and JND-tojc).

Separate analyses were performed for the young and elderly groups to capture age-specific differences in the predictive relationships. The stepwise forward method allowed for the progressive inclusion of predictors based on their statistical contribution to the model, ensuring that only those with a significant impact were retained.

This approach identified the predictors most strongly associated with each physical health dimension within each age group. The results highlight the unique contributions of interoceptive and multisensory integration variables to physical health outcomes, emphasizing their differing roles across the lifespan. Only statistically significant findings are reported, focusing on the most relevant predictors for understanding physical functioning and health in young and elderly populations.

4. Results

In the elderly group, the multiple regression analyses with Physical Functioning (SF-36) as criterion showed a model with 5 predictors: $F(8, 14) = 5.473$, $p = .002$, $R = 0.87$, $R^2 = 0.76$. To graphically represent the goodness of the model, a graph comparing the observed and predicted values has been included (Figure 2, where the alignment of points near the red line suggests a strong predictive ability of the model).

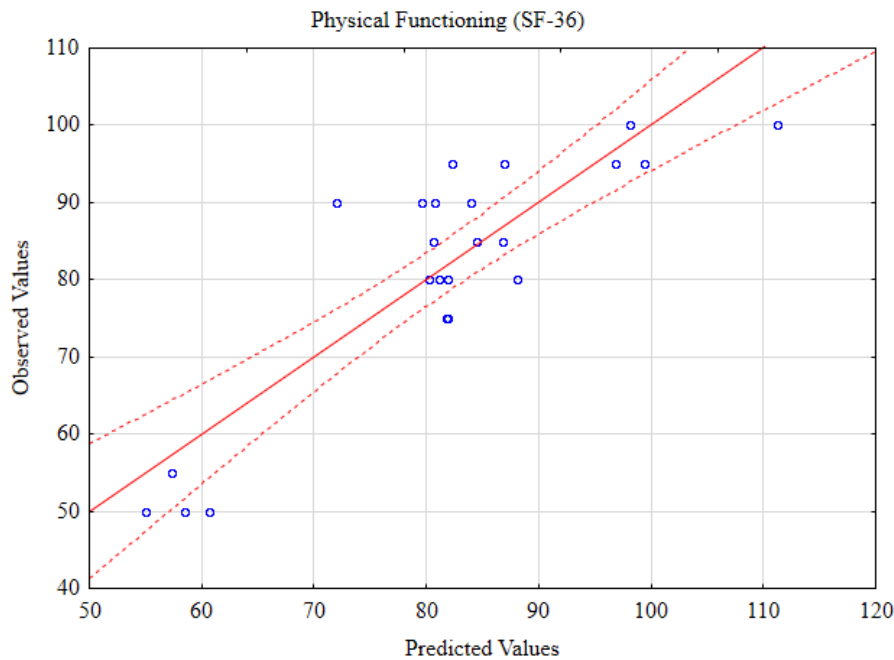


Figure 2. Graph shows Observed vs. predicted values from the stepwise forward regression model with Physical Functioning as a criterion.

The predictors Aw-c, Aw-d, M4 and M6 (Maia), and JND-sj contributed significantly to the model (see Table 2): the higher the interoceptive sensibility and awareness (Aw-c; Aw-d; M4; M6;), the higher the perceived physical functioning. Conversely, the lower multisensory temporal resolution (JND-sj), the lower the perceived physical functioning. Indeed, for the JND-sj, the higher the score, the worse the performance. No multiple regressions with combination of interoceptive and multisensory integration predictors emerged for young people.

Table 2. The table shows the effect of predictors that contributed significantly to the model in relation to physical functioning as a criterion.

Physical Functioning (M = .82)					
	Mean	B	Std. Err.	t	p
Aw-c	0.64	0.36	0.15	2.292	.03*
Aw-d	0.68	0.59	0.18	3,124	.007**
M4	2.85	0.80	0.20	3.822	.001***
M6	2.89	-1.04	0.30	-3.455	.003**
JND-sj	255.60	-.44	0.14	-3.004	.009**

*** p < .001; ** p < .01; * p < .05.

In the elderly group, the multiple regression analysis with Role limitations due to physical health (SF-36) as criterion showed a model with 4 predictors: $F(6, 16) = 8.334$, $p = .0003$, $R = 0.87$, $R^2 = 0.75$. To visually represent the quality of the model, a graph comparing the observed and predicted values has been included (Figure3, where the alignment of points near the red line suggests a strong predictive ability of the model).

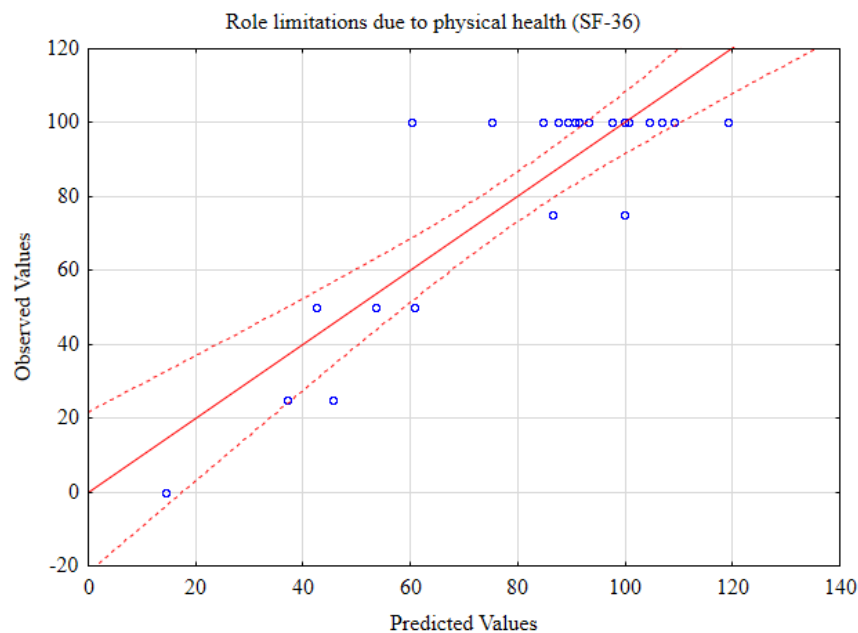


Figure 3. Graph shows Observed vs. predicted values from stepwise forward regression model with Role limitations due to physical health as a criterion.

The predictors Aw-c, M8 (Maia), JND-sj, and JND-tojc contributed significantly to the model (see Table 3): the higher the interoceptive sensibility and awareness (Aw-c; M8), the higher the score on the role limitations scale due to physical health (hence fewer perceived limitations). In contrast, the lower multisensory temporal resolution and temporal tactile acuity (JND-sj; JND-tojc), the lower the score on the role limitations scale due to physical health (so more perceived limitations).

Table 3. The table shows the effect of predictors that contributed significantly to the model in relation to Role limitations due to physical health as a criterion.

Role limitations due to physical health (M = .82)					
	Mean	b*	Std. Err.	t	p
Aw-c	0.64	0.38	0.14	2.650	.01*
M8	3.87	0.58	0.15	3.682	.002***
JND-sj	255.60	-0.53	0.13	-3.854	.001***
JND-tojc	99.01	-0.30	0.13	-2.205	.04*

*** p < .001; ** p < .01; p < .05.

No multiple regressions with combination of interoceptive and multisensory integration predictors emerged for young people. There were no significant effects for both the elderly and the young on the Energy/Fatigue and General Health criteria.

5. Discussion

Functional and physical limitations in aging are risk factors for future disability and institutionalization (Onder et al., 2005; Paterson et al., 2004). Given the increasing proportion of elderly people in the Western countries, understanding what factors may contribute to predicting such limitations is an important public health endeavor, and a goal for maintaining an independent lifestyle for as long as possible.

To address this issue, we evaluated a group of young and elderly individuals using the Short Form Health Survey 36 questionnaire (SF-36) (Ware and Sherbourne 1992; Italian version, Apolone et al., 1998), to assess the daily life functioning. Additionally, to evaluate age-related changes in interoception, we employed multiple measures to assess the objective and subjective components of interoception. Participants completed the MAIA questionnaire, followed by the Schandry and Tapping tasks to assess interoceptive dimensions. Finally, to assess multisensory integration, participants performed the Simultaneity Judgment (SJ) task and the Temporal Order Judgment (TOJ) task, with crossed and uncrossed hands (Pasciucco et al. 2025; Sarko et al., 2012a; Sarko et al., 2012b; Laasonen et. al, 2001). In the elderly group, multiple regression analysis with Physical Functioning (SF-36) as the dependent variable identified a model with five significant predictors: Maia - M4 and M6, Aw-c, Aw-d and JND-sj. These results highlight the significant contributions of interoceptive sensibility, awareness and multisensory temporal resolution to perceived physical functioning.

More specifically, results demonstrated a positive correlation between interoceptive sensibility and awareness (M4, Attention Regulation; M6, Self-Regulation; Aw-c; Interoceptive Awareness-Counting task; Aw-d; Interoceptive Awareness- Detection task) and perceived physical functioning, with higher interoceptive sensibility and awareness associated with better physical functioning. These findings align with previous research emphasizing the pivotal role of interoceptive awareness in

shaping perceptions of physical well-being (Wallman-Jones et al., 2021). While it is well-documented that interoceptive sensitivity declines with age—older adults often exhibit reduced interoceptive awareness (Khalsa et al., 2009a; Ulus & Aisenberg-Shafran, 2022)—our results suggest that preserved interoceptive awareness can act as a protective factor for perceived physical health.

Older adults with higher levels of interoceptive awareness report better physical functioning, likely due to their enhanced ability to recognize and interpret bodily sensations. This heightened awareness may facilitate more effective regulation of physical activity and overall health, enabling these individuals to adapt to the physiological changes that accompany aging. Furthermore, this capacity might explain why some older adults, despite inevitable declines in certain sensory and physical abilities, perceive themselves as having higher levels of physical functioning. These findings highlight the potential importance of fostering interoceptive sensitivity to support well-being in later life.

Conversely, reduced multisensory integration (as indicated by JND-sj scores, where higher scores represent poorer performance) were associated with lower perceived physical functioning. Difficulties in processing and integrating sensory information from the external environment can adversely impact physical performance and overall health perception. Multisensory integration is crucial for accurately perceiving and responding to external stimuli, playing a fundamental role in daily activities (de Dieuleveult et al., 2017). Impairments in this area can negatively impact physical capabilities in older adults. In line with this, previous studies have shown that age-related deficits in multisensory integration can contribute to physical limitations and a diminished sense of functional ability (Diaz & Yalcinbas, 2021; Seghier, 2013). For instance, impaired multisensory integration can increase the risk of falls among older adults (Mahoney et al., 2019; Zhang et al., 2020), further highlighting the importance of sensory processing for maintaining physical functioning in aging populations.

No significant multiple regression models combining interoceptive and multisensory integration predictors were identified for younger adults. This absence of significant interactions suggests that these factors may influence the perception of physical health differently in younger individuals compared to older adults. This disparity could reflect developmental or age-related variations in how sensory processing contributes to the perception and regulation of physical functioning, potentially indicating a lesser reliance on these sensory domains in younger populations.

In the elderly group, multiple regression analysis using Role limitations due to physical health (SF-36) as dependent variable showed a model with four significant predictors: Maia-M8, Aw-c, JND-sj and JND-tojc. Higher interoceptive sensibility and awareness (M8; Aw-c) was associated with higher scores on the role limitations due to physical health scale, indicating fewer perceived physical

limitations. In contrast, reduced multisensory temporal sensitivity, as indicated by higher JND-sj and JND-tojc scores were linked to lower scores on the role limitations scale, reflecting greater perceived limitations in physical functioning. No significant regression models emerged for younger adults when combining interoceptive and multisensory integration predictors.

These data suggest that, in older adults, a stronger connection with internal bodily signals (higher interoceptive sensibility and awareness) fosters a more positive perception of their physical state. However, difficulties in processing external sensory information and integrating it effectively leads to a worse perception of physical functioning and increased awareness of limitations.

Taken together, these results are consistent with existing models of successful ageing, which propose that older adults are less likely to maintain good functionality in daily life when they perceive significant motor or sensory limitations (Lowry et al., 2012). This highlights the critical role of sensory processing in shaping older adults' subjective experiences of physical health and their ability to adapt to age-related changes.

From a neurocognitive and neurofunctional view, examining the brain regions involved in these processes provides insight into the compensatory strategies that older adults employ to maintain performance despite age-related declines in multisensory and interoceptive processing. For instance, neuronal loss, microinfarcts, and white matter alterations have been linked to daily physical activity in older adults, with the integrity of regions such as the insula, precentral and postcentral gyri, and white matter tracts strongly associated with physical activity levels near the end of life (Buchman et al., 2018). Although older and younger adults demonstrate similar behavioural responses to multisensory stimuli, neuroimaging reveals distinct patterns of brain activity. Younger adults show greater activation in sensory-specific regions like the superior temporal gyrus and calcarine fissure, whereas older adults increasingly rely on dorsal frontal and parietal areas, indicating compensatory recruitment of regions involved in executive functions and attention (Diaz et al., 2021). Additionally, the angular gyrus plays a pivotal role in multisensory integration in older adults, serving as a hub for sensory convergence (Seghier, 2013; Hirst et al., 2021).

Interoceptive processing, critical for physical functioning, engages regions such as the insula, anterior cingulate cortex, and medial prefrontal cortex, with the Salience Network playing a key role in prioritizing interoceptive signals (Ueno et al., 2020; Wu et al., 2024). The insula emerges as a central structure linking interoception with daily functioning, while frontal, parietal, and angular gyrus regions support compensatory multisensory strategies. This intricate interplay reflects the adaptive complexity of sensory and interoceptive systems in aging, underscoring the brain's ability to reallocate resources to maintain functional performance.

To sum up, aging-related changes in multisensory interoceptive processing are accompanied by an increase in physical limitations, such as self-reported autonomic movement difficulties. These changes can have a significant impact on the ability to perform daily activities, reducing overall quality of life (Mullen et al., 2012; Rejeski & Mihalko, 2001; Stuifbergen et al., 2006). Indeed, our study highlights the critical interaction between exteroceptive dimensions and multisensory temporal processing, demonstrating their significant role in influencing the perception of physical well-being. The integration of contributions from different aspects of exteroceptive and interoceptive dimensions in examining physical functioning in different age groups represents a novel aspect of this study. This approach provided a more comprehensive and detailed understanding of how these factors interact to shape perceptions of physical functioning, particularly in older adults.

CHAPTER 6

1. General Discussion

The main aim of this thesis was to develop, implement, and validate a novel multidimensional battery for assessing exteroceptive and interoceptive bodily dimensions. Grounded in embodied cognition and predictive coding theories, the battery was designed to capture a wide range of bodily dimensions, including body image, spatial tactile acuity, body structural representation, multisensory temporal resolution, multisensory integration, peripersonal space, temporal tactile acuity, sensorimotor functions, and interoceptive accuracy, sensibility, and awareness. This approach allowed us also to implement a machine learning approach to systematically evaluate the interactive and distinct contributions of bodily processes to various condition related to physical and mental well-being.

The four studies presented in this thesis explored the role of interoceptive and exteroceptive bodily dimensions to different domains: schizotypy, affective disorders (anxiety and depression), and aging. In Study 1, we investigated the relationship between bodily processes and schizotypal personality traits. This study explored how interoceptive and exteroceptive bodily dimensions predict schizotypal personality traits (cognitive-perceptual, interpersonal, disorganized). Using a multivariate predictive approach (PLSR), we identified both specific and shared bodily contributions. Cognitive-perceptual traits (positive-like symptoms) were specifically predicted by altered multisensory temporal processing, suggesting impairments in integrating external sensory inputs over time. Interpersonal traits (negative-like symptoms) were predicted by peripersonal space, multisensory integration, and interoceptive dimensions (accuracy and sensibility), highlight the disturbances in bodily self-awareness and social/emotional processing. Disorganization traits showed no specific bodily predictors, suggesting they may be more closely linked to cognitive deficits than to altered bodily processing. Non-specific predictors (common to multiple traits) included exteroceptive dimensions such as body image, spatial tactile acuity, body structural representation, and sensorimotor functions. These may reflect a basic bodily vulnerability across the schizotypal spectrum. Overall, the findings support the idea that bodily alterations are differentially linked to schizotypal traits, offering novel insights into early markers of psychosis vulnerability.

In Study 2, we investigated the predictive contribution of interoceptive and exteroceptive bodily dimensions to anxiety and depression. By using PLSR, we identified both shared and specific predictors across separate and combined models. For depression, only body image, specifically bodily uneasiness, was a significant predictor, suggesting that subjective discomfort with one's own body is sufficient to predict depressive symptoms. This aligns with previous findings linking depression to persistent physical discomfort and negative bodily self-perception. In contrast, anxiety was associated

with a broader range of exteroceptive dimensions, including not only body image but also spatial tactile acuity, body structural representation, multisensory processing, and sensorimotor functions. This indicates that anxiety is characterized by a more pervasive alteration in the processing of external bodily signals. Both anxiety and depression shared predictors such as interoceptive accuracy and interoceptive sensibility (Acc-c, BPQ-SUP, 8M trusting), supporting the idea that interoceptive disturbances are a common vulnerability factor in emotional disorders. However, specific patterns emerged: anxiety was uniquely predicted by sensibility items reflecting heightened body monitoring (2M not-distracting, 7M body listening), suggesting a state of hypervigilance. Depression, instead, was associated with difficulties in emotional and self-regulation (4M attention regulation, 6M self-regulation), consistent with emotional disconnection and affective blunting. When interoceptive and exteroceptive predictors were considered together, body image and interoceptive sensibility remained robust predictors of both disorders, suggesting a core bodily vulnerability. However, for anxiety, exteroceptive features (sensorimotor and structural representations) also remained significant, supporting a dual hyper-attentiveness to both internal and external signals. For depression, the predictive pattern was narrower and centred on discomfort and internal disengagement.

In Study 3, we applied the same battery to a sample of older adults and investigated whether interoceptive and multisensory processing could predict daily physical functioning. To this aim we employed a two-step analysis. In the first step we found that interoceptive sensibility was the most relevant predictor of some aspects of daily functioning. It significantly contributed to physical and emotional role limitations, energy/fatigue, and emotional well-being. These results suggest that subjective interoceptive sensibility, rather than objective detection of internal signals, is more directly associated with how older adults perceive their daily functioning, because sensibility reflects a broader integration of body-related emotional and cognitive processing. In the second step, we tested the interaction of the significant interoceptive predictors with the exteroceptive dimension. Our result show that both internal and external body signals contribute to daily functioning. In conclusion, this study shows that interoceptive sensibility is a central predictor of emotional and physical functioning in aging, and that combining it with exteroceptive dimensions allows for a more complete understanding of how older adults maintain autonomy and well-being. These findings support the development of targeted, body-focused interventions to promote healthy and active aging.

In Study 4, we explored how interoceptive and multisensory processing, assessed through a reduced set of tasks, predicted physical functioning in older adults, compared to younger participants. Results confirmed that age-related decline in interoception and multisensory temporal sensitivity significantly impacted self-reported quality of daily functioning, suggesting that perceptual bodily processing may be a core component of aging-related changes.

Together, the four studies provide converging evidence that bodily dimensions, both interoceptive and exteroceptive dimensions, are central across different psychological conditions and life stages.

Moreover, the results of these studies demonstrate the reliability, flexibility, and applicability of the battery across diverse psychological and physical conditions. By employing the battery and the methodology described, we successfully replicated findings from previous literature. In Study 1, specific contributions of bodily processes to distinct schizotypal traits emerged: multisensory temporal resolution was specifically associated with cognitive-perceptual traits, interoceptive accuracy and peripersonal space predicted interpersonal traits, while disorganization showed no specific bodily predictors. These findings not only align with previous literature (e.g. Di Cosmo et al., 2021, Ardizzi et al., 2020) but also validate the capacity of the battery to detect trait-specific patterns, reinforcing its utility for identifying early vulnerability markers along the psychosis spectrum. In Study 2, the battery replicated well-established findings, such as body image dissatisfaction in depression (Paans et al., 2018; Pylvänäinen et al., 2021) and interoceptive hypervigilance in anxiety (Pollatos et al., 2007; Dunn et al., 2010), while also identifying novel predictors, including sensorimotor and structural body representations in anxiety, and emotional self-regulation dimensions in depression. In Study 3, we found that interoceptive sensibility was the strongest predictor of daily functioning in older adults. These results suggest that subjective integration of bodily signals plays a key role in physical and emotional resilience during aging. In the second step of the analysis, the inclusion of exteroceptive predictors significantly improved model, showing how bodily perception in aging depends on the interaction between internal and external signals. Finally, in Study 4, using a reduced set of tasks, we replicated and extended these findings. Specifically, we confirmed that age-related declines in interoception and multisensory temporal resolution are associated with poorer physical functioning, as measured by the SF-36. These results support the battery's flexibility and adaptability showing that it can be applied to different age groups and conditions, and that specific components can be used independently depending on the study aims.

The use of Partial Least Squares Regression (PLSR) enabled the integration of multiple bodily predictors, addressed multicollinearity, and provided interpretable, generalizable models for linking bodily dimensions to clinical symptoms and functional outcomes. This machine learning approach was essential for capturing the complexity and interdependence of bodily processes.

In terms of validity, the battery showed high conceptual coherence, sensitivity in detecting both specific and shared predictors, and replication of known effects. At the same time, it allowed for the identification of novel predictors in under-investigated domains, supporting its explorative role.

In sum, this thesis provides a novel and validated framework for studying the embodied well-being. The multidimensional battery offers both theoretical insight and practical utility, advancing our understanding of how bodily processes shape psychological functioning across the lifespan and across clinical and non-clinical populations.

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