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Emerging effects of temperature on human cognition, affect, and behaviour

Susanne Fischer[a,*], Kathrin Naegeli[b], Daniela Cardone[c], Chiara Filippini[c], Arcangelo Merla[c], Kay-Uwe Hanusch[d], Ulrike Ehlert[a]

[a] University of Zurich, Institute of Psychology, Zurich, Switzerland
[b] University of Zurich, Department of Geography, Zurich, Switzerland
[c] University G. d'Annunzio of Chieti-Pescara, Department of Engineering and Geology, Chieti, Italy
[d] Bern University of Applied Sciences, Department of Health Sciences, Berne, Switzerland

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ABSTRACT

Human body core temperature is tightly regulated within approximately 37 °C. Global near surface temperature has increased by over 1.2 °C between 1850 and 2020. In light of the challenge this poses to human thermoregulation, the present perspective article sought to provide an overview on the effects of varying ambient and body temperature on cognitive, affective, and behavioural domains of functioning. To this end, an overview of observational and experimental studies in healthy individuals and individuals with mental disorders was provided. Within body core temperature at approximately 37 °C, relatively lower ambient and skin temperatures appear to evoke a need for social connection, whereas comparably higher temperatures appear to facilitate notions of other as closer and more sociable. Above-average ambient temperatures are associated with increased conflicts as well as incident psychotic and depressive symptoms, mental disorders, and suicide. With mild hypo- and hyperthermia, paradoxical effects are observed: whereas the acute states are generally characterised by impairments in cognitive performance, anxiety, and irritability, individuals with depression experience longer-term symptom improvements with treatments deliberately inducing these states for brief amounts of time. When taken together, it has thus become clear that temperature is inexorably associated with human cognition, affect, and (potentially) behaviour. Given the projected increase in global warming, further research into the affective and behavioural sequelae of heat and the mechanisms translating it into mental health outcomes is urgently warranted.

1. Introduction

The optimal circadian human body core temperature, defined as visceral, blood, and brain temperature, for cellular functioning is at approximately 37 °C (Romanovsky, 2018). At body core temperatures of below 0 °C cell function is lost due to the freezing of water, whereas above 45 °C, enzymes start to denature. As demonstrated by animal experiments, at innocuous temperatures between 15 °C and 45 °C, thermoceptive neurons located in the skin and in mucous membranes relay to the brain via two pathways: The spinothalamic pathway (Craig., 2018; Craig et al., 2000) and the spinoparabrachial pathway (Morrison, 2016; Morrison and Nakamura, 2019; Nakamura, 2011). Signals transmitted via the former pathway terminate in the contralateral dorsal posterior insula to activate behavioural thermoregulation (e.g., seeking warmer/colder environments, adding/removing layers of clothing). Signals relayed via the latter pathway terminate in the preoptic area of the anterior hypothalamus, where they are integrated with thermal signals from the brain, the viscera, and deep somatic tissue to activate autonomic thermoregulation (see also Fig. 1). As mostly determined by animal experiments, in the case of cold, the activity of warm-sensitive neurons is inhibited by cold receptors in the skin (TRPM8, TRPA1), which leads to a higher activity of warm-insensitive neurons (Benarroch, 2007; Nakamura, 2011; Patapoutian et al., 2003). In humans, this eventually results in cutaneous vasoconstriction and piloerection to prevent heat loss and brown adipose tissue activation and shivering to generate heat (Johnson and Kellogg, 2018). As mostly determined by animal experiments, in the case of warmth/heat, warm-sensitive neurons are activated via warm receptors in the skin (TRPV4, TRPV1) (Benarroch, 2007; Nakamura, 2011; Patapoutian et al., 2003). In humans, this leads to cutaneous vasodilation and sweating to facilitate

* Correspondence to: University of Zurich, Institute of Psychology, Clinical Psychology and Psychotherapy, Binzmuehlestrasse 14 / Box 26, 8050 Zurich, Switzerland.

E-mail address: s.fischer@psychologie.uzh.ch (S. Fischer).

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heat loss (Cramer et al., 2022).

Climate change has posed a challenge for the human thermal system. Global near surface temperature has increased by over 1.2 °C between 1850 and 2020, with the largest increase observed after 1990 (Intergovernmental Panel on Climate Change, 2021), and, as a result, extreme weather events are projected to increase in both frequency and intensity (e.g., Guo et al., 2018). Both temperatures below and above indifferent ambient temperatures have the potential to challenge the thermal system and cause cold/heat stress. Research in somatic diseases has already demonstrated that cold spells constitute a risk factor for mortality due to some of the most burdensome chronic somatic diseases, namely cardiovascular and respiratory diseases, and most likely by increases in blood pressure, blood viscosity, cholesterol, platelet and red blood cell count, dehydration as well as rhinorrhoea and bronchoconstriction (Ryti et al., 2016). Likewise, above-average ambient temperatures and heat waves have been linked with morbidity and mortality related to cardiovascular (Liu et al., 2022) and respiratory diseases (Cheng et al., 2019). The underlying mechanisms are far from being completely understood, but presumably include compromised cardiac oxygen delivery, dehydration, immune responses to cell death, and increased air pollution (Ebi et al., 2021). By contrast, relatively little is still known about the effects of changes in ambient temperature on mental disorders, let alone on potential underlying mechanisms.

Interestingly, evidence is now emerging for individuals with mental disorders to exhibit alterations in thermoregulation. For instance, individuals with schizophrenia appear to be characterised by deficient heat loss (Chong and Castle, 2004). Similarly, emerging evidence suggests that depressed individuals report greater subjective difficulties in adjusting to warmth when compared to non-depressed individuals (von Salis et al., 2021). This finding is mirrored by evidence for reduced sweating in the same population (Raison et al., 2015). Conversely, there is tentative evidence for increased sweating in some forms of anxiety disorders, albeit sparse and warranting replication (Fischer et al., 2021). Nevertheless, these preliminary findings suggest that individuals with mental disorders are disproportionately affected by changes in average ambient temperatures and extreme weather events. The latest Global Burden of Disease Study estimated that 12,262 in 100,000 people suffer from mental disorders globally, with depressive and anxiety disorders comprising over half of all cases (Global Burden of Disease 2019 Mental Disorders Collaborators., 2022). Given these numbers and the fact that these disorders are already the second-leading cause of Years Lived with Disability, it seems important to learn more about how temperature affects psychological function domains, which are key to mental health and causative for the development and exacerbation of mental disorders in the case of significant disturbances.

The aim of this perspective article was to provide an overview of the role of temperature in human cognition, affect, and behaviour, including emerging implications for mental health. Priority will be given to meta-analytical evidence and evidence from systematic reviews, with narrative reviews and original research integrated in the case that systematic summaries are lacking. We will start out with some of the most frequently replicated findings regarding the psychological implications of exposure to different ambient temperatures before moving on to psychological effects of changes in body temperature. We will include work conducted in both healthy adults and in individuals with mental disorders, and will integrate observational and (quasi-)experimental evidence. A third chapter will discuss potential biological mechanisms underlying these psychological effects. The perspective article will conclude by means of a graphical summary of the most important findings and will outline directions for future basic and clinical research, with a focus on promising research avenues for biological psychology.

2. Psychological effects of changes in ambient temperature

Whole-body exposure to ambient temperature occurs both outdoors and indoors, with thermosensation closely tied to meteorological factors such as solar radiation, relative humidity, precipitation, and wind speed. In the following subchapters, systematic evidence from observational studies, which were mostly population-based, will be summarised first, followed by systematic evidence from (quasi-)experimental studies, which were mostly laboratory- or hospital-based. Within each subchapter, the evidence of ambient cold on cognition, affect, behaviour, and/or mental health will be outlined first, followed by the effects of ambient warmth and heat.

2.1. *Findings from observational studies*

The observational evidence for psychological effects of exposure to cold ambient temperatures is relatively sparse and concentrated on mental health. The most comprehensive meta-analysis to date has found that extreme cold, that is, daily temperatures in the 1st and 2.5th percentile, do not constitute a risk factor for the development or exacerbation of mental disorders (Li et al., 2023). Notably, the studies included in the meta-analysis varied to a great extent in whether they used concurrent or time-lagged correlations between temperature and mental health. Moreover, the subgroup of time-lagged studies varied in the lag time/exposure prior to outcome, rendering it possible that cold might, at specific times and for specific durations, exert subtle effects on mental health, which were not detected in the meta-analysis due to the scarce and heterogenous data base. By contrast, populations of countries

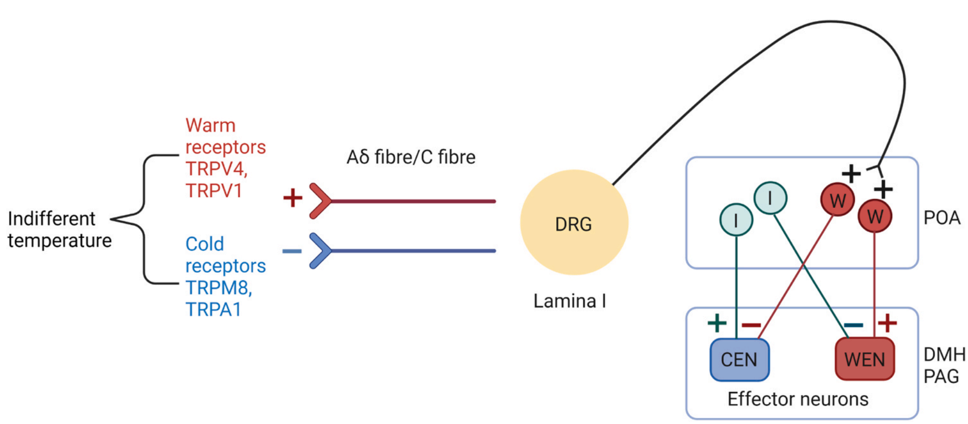

Fig. 1. Illustration of the spinoparabrachial pathway governing autonomic themoregulation. CEN = cold effector neurons; DMH = dorsomedial hypothalamus; DRG = dorsal root ganglion; I = warm-insensitive neurons; PAG = periaqueductal grey; POA = preoptic area; TRPM8 = transient receptor potential cation channel subfamily M member 8; TRPV1 = transient receptor potential cation channel subfamily V member 1; TRPV4 = transient receptor potential cation channel subfamily V member 4; W = warm-sensitive neurons; WEN = warm effector neurons. Figure created with biorender.com.

in which the coldest month is comparably warm are, on average, happier than populations of countries in which the coldest month comparably cold (Rehdanz and Maddison, 2005).

The observational evidence for psychological effects of ambient warmth and heat is slightly more comprehensive. Countries in which the hottest month is comparably cold are happier than countries in which it is comparably warm (Rehdanz and Maddison, 2005). Conversely, at above-average temperatures, there is a robust relationship between increases in temperature and interpersonal and intergroup conflict (Burke et al., 2015). Notably, the contemporaneous effects were significantly larger than the lagged time effects. In line with these findings, the warmer the daily temperature in psychiatric wards the more pronounced the concurrent symptoms patients with schizophrenia experience (Tham et al., 2020). Moreover, a meta-analysis has shown that daily temperatures in the 99th percentile and heatwaves, defined as three subsequent daily maximum temperatures of at least 35 °C, are associated with a 2% and 9.7% increase in the risk for hospital admissions due to mental disorders, respectively (Thompson et al., 2023). Moreover, according to the same analysis, a 1 °C increase in daily temperature is associated with a 1.7% increases in suicide. Again, this meta-analysis was not able to differentiate between different exposure-outcome time lags, which means it remains unclear whether specific time points and durations during which heat is experienced are particularly detrimental to mental health outcomes.

2.2. Findings from (quasi-)experimental studies

Experimental evidence for psychological effects of cold ambient temperatures exists in the cognitive and mental health domain. In mental disorders, clinical trials have begun to test the efficacy of whole-body cryotherapy. This treatment usually lasts one to five weeks and comprises six to 30 exposure sessions, during which patients spend 20 to 60 s in an − 60 °C to − 10 °C tempered atrium, followed by 30 to 180 s in a − 195 °C to − 110 °C chamber (Tabisz et al., 2023). According to a meta-analysis, whole-body cryotherapy exerts medium- to large-sized effects in terms of enhancing well-being and alleviating depressive symptoms (Doets et al., 2021). In healthy adults, the exposure to cold chamber air temperatures of between − 10 °C and 10 °C for between 30 to 120 min is associated with significant impairments in attention, processing speed, memory, and executive function, but not reasoning (Falla et al., 2021). Moreover, in temperate climate zones, being exposed to outdoor and indoor temperatures below 20 °C for minutes/hours appears to trigger nostalgia, a greater desire to be with others, and the seeking of social contact compared to warmer temperatures (IJzerman et al., 2015).

The experimental evidence base for psychological effects of warm and hot ambient temperatures is, again, slightly broader. In healthy adults in temperate climate zones, being exposed to indoor temperatures between 22 °C and 24 °C for minutes is followed by a more relational focus and feel closer to others when compared to cooler room temperatures (IJzerman et al., 2015). By contrast, a recent meta-analysis was neither able to confirm the frequently stipulated "warmth-primes-prosociality" hypothesis nor the equally popular "heat-facilitates-aggression hypothesis" (Lynott et al., 2023). This meta-analysis did not investigate the effects of exposure duration, which means there remains a possibility that specific durations of warmth/heat exposue map onto more prosocial/aggressive behaviour. Outdoor and indoor temperatures above 25.7 °C are related to significantly impaired cognitive performance, with more pronounced negative effects with increasing exposure times and in perceptual tasks, and with task accuracy first affected

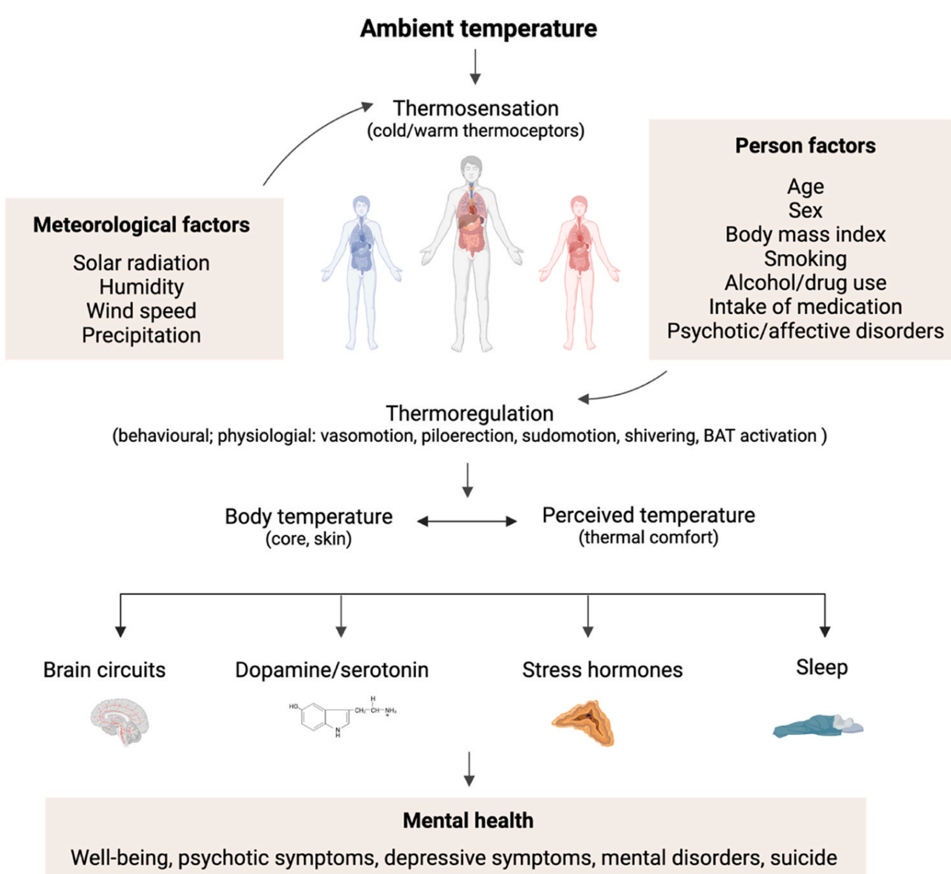

Fig. 2. Illustration of the hypothesised mechanisms translating ambient/body temperature into mental health outcomes. BAT refers to brown adipose tissue. Figure created with biorender.com.

followed by response time (Hancock et al., 2007). In individuals with mental disorders, mild to moderate whole-body hyperthermia is increasingly used as a treatment (Knobel et al., 2022). This can comprise one single multiple-hour sessions in which heat is applied by means of infrared lights and heating coils (Heckel Medizintechnik GmbH, Esslingen, Germany, and Hydrosun Medizintechnik GmbH, Mullheim, Germany), which creates chamber temperatures of around 57 °C. According to a systematic review, large-size reductions in depressive symptoms are observed with this type of treatment (Hanusch and Janssen, 2019).

3. Psychological effects of changes in body temperature

Body temperature can be divided in to skin and body core temperature, with thermoregulation heavily influenced by person factors, such as age, sex, Body Mass Index, smoking, alcohol/drug consumption, and medication intake. In the following subchapters, systematic evidence from observational studies, which have investigated individuals in hypothermic, normothermic, and hyperthermic states, will be summarised first, followed by systematic evidence from experimental studies, which have subjected individuals to physical interventions that are capable of modifying skin and body core temperature. Within each subchapter, the effects of low body temperatures on cognition, affect, behaviour, and/or mental health will be outlined first, followed by an outline of the effects of high body temperatures.

3.1. Findings from observational studies

The observational evidence for psychological effects of low body temperature is concentrated on the cognitive domain. During severe hypothermia, when environmental exposure or illnesses cause body core temperature to fall below 28 °C, individuals reach a state of unconsciousness (Paal et al., 2018). At moderate levels of hypothermia, when body core temperature ranges between 28° and under 32 °C, steady decreases in consciousness are observed. At mild levels of hypothermia, when body core temperature ranges between 32 °C and just under 35 °C, individuals demonstrate impaired judgment, anxiety, irritability, and inappropriate behaviour (e.g., paradoxical undressing).

The observational evidence for psychological effects of high body temperatures is more extensive. Increases in body core body temperature of approximately 0.1 °C are, for example, observed in association with hot flushes during the perimenopause, and have been linked with depressive symptoms (Natari et al., 2018). In line with this finding, researchers have observed significantly elevated body core temperature in individuals with depressive episodes as compared to healthy controls (Raison et al., 2015). At body core temperatures between 37 °C and 40 °C, heat exhaustion occurs, which is characterised by poor judgment and irritability (Kenny et al., 2018). Body core body temperatures greater than 40 °C are defined as heat stroke, which resembles severe hypothermia in the sense that individuals are delirious or in a state of coma (Al Mahri and Bouchama, 2018).

3.2. Findings from (quasi-)experimental studies

The experimental evidence for psychological effects of cold body temperatures is sparse and focused on cognition. Specifically, it appears that cold-chamber induced skin temperatures between 19 °C and 24.5 °C and body core temperatures between 36 °C and 36.9 °C are related to reduced vigilance and reduced planning accuracy (Falla et al., 2021).

Experimental evidence for psychological effects of warm body temperatures is also still in its infancy, but has evolved to a slightly greater extent. In healthy adults, some authors find that applying warm stimuli to the skin is followed by a more relational focus as well as by perceiving others as closer and as more sociable (IJzerman et al., 2015). By contrast, warmth does not appear to affect social behavioural outcomes according to a recent meta-analysis (Lynott et al., 2023). In individuals with mental disorders, emerging findings indicate that the higher body core temperatures, which can range up to 39.3 °C, during moderate whole-body hyperthermia, the more pronounced the long-term reduction in depressive symptoms (Hanusch and Janssen, 2019).

4. Mechanisms

As summarised above, states in which body core temperatures is between 35 °C and 37 °C are characterised by deficits in attention and executive function. Although little is still known about the mechanisms translating cold into cognitive difficulties, a biological explanation is that acute changes in brain vasoconstriction mediate cognitive deficits upon cold exposure (Muller et al., 2012). In line with this notion, empirical findings of tyrosine supplementation reversing the cold-induced effects in memory suggest an involvement of brain catecholamines (Mahoney et al., 2007; O'Brien et al., 2007). Another, more psychological hypothesis is that these effects result from the distraction caused by thermal discomfort (Falla et al., 2021).

Moving along the thermal spectrum into the normothermic state, we have seen that the effects of temperature on cognition, affect, and behaviour are more subtle and contextual. With body core temperature at around 37 °C, comparably lower ambient/skin temperatures appear to evoke nostalgic feelings and a desire for social contact. Comparably higher ambient/skin temperatures, on the other hand, induce perceptions of other people as being closer and more sociable. From a neurobiological point of view, these links between temperature and social cognition can be explained by activation of the contralateral dorsal posterior insula through changes in skin temperature, which subsequently spreads to the contralateral middle and anterior insula (Craig, 2002, 2009, 2018; Craig et al., 2000). The activation of this area is paralleled by affective awareness of interoceptive cues, such as temperature, in other words, by "feelings" of cold/warmth. This feeling may subsequently guide social cognition and behaviour by means of projections to the adjacent orbitofrontal cortex and pregenual anterior cingulate. Indeed, empirical research has repeatedly identified the insula as a key area of shared activation upon probing individuals with both temperature cues (e.g., holding a warm beverage) and with social connection cues (e.g., viewing pictures of significant others) (Inagaki and Eisenberger, 2013; Inagaki et al., 2019). Given that the insula is densely populated with μ-opioid receptors, and that μ-opioids are involved in both thermosensation/-regulation (Adler et al., 1988; Clark, 1979) and social connectedness (Inagaki, 2018; Panksepp, 1998; Panksepp et al., 1980), it seems possible that μ-opioids are mediators of the above described process. Indeed, empirical research has demonstrated that administering naltrexone erased social connectedness in response to warmth stimulation (Inagaki et al., 2019; Inagaki et al., 2015). Alternatively, from a more psychological perspective, the social connotations of cold vs. warm temperatures guide social cognition. This hypothesis is supported by linguistic phrases such as "they are cold-blooded" or "they are warm-hearted" (Fiske et al., 2007).

Moving towards the upper end of the thermal spectrum, ambient temperatures of above 25 °C are associated with impaired cognition, the above reviewed findings suggest that ambient temperatures of above 35 °C are associated with interpersonal and intergroup conflicts, psychotic and depressive symptoms, mental disorders, and suicide. However, although these effects are stronger upon longer exposures, it is unclear whether by actual increases in body core temperature. Key purported mechanisms include difficulties with brain cooling and oxygenation, changes in brain circuits involved in cognition, and/or a concentration of cerebral blood flow to areas involved in thermoregulation and away from areas involved in cognition/emotion regulation (e.g., Gaoua et al., 2017; Gaoua et al., 2011; Lohmus, 2018; Nakata et al., 2021). Another potential mechanism are heat-induced increases in circulatory levels of dopamine and serotonin (Lohmus, 2018). While the former is in line with the excessive central dopamine which typifies psychotic disorders (e.g., Howes and Murray, 2014), the latter appears to contradict the popular notion of serotonin depletion in depressive disorders (e.g., Jauhar et al., 2023). However, the exact location of heat-responsive dopaminergic and serotonergic neurons as well as their role in mental health has yet to be identified. Regarding serotonin, research in animals, however, already suggests that a subset of serotonergic neurons in the dorsal raphe nucleus may act as a key node for ambient and body core warmth/heat to translate in to altered cognition and mood (Lowry et al., 2009). A third purported mechanism is an increase in catecholamines and cortisol (Lohmus, 2018). Elevated circulating concentrations of these hormones are some of the most well established findings in mental disorders (e.g., Fischer and Ehlert, 2019; Maletic et al., 2017; Stetler and Miller, 2011) and it is thus conceivable that heat stress may foster symptom development. A fourth mechanism is disturbed sleep (Lohmus, 2018). An intricate interplay between steady decreases in body core temperature and increases in skin temperature is indeed instrumental for the initiation of sleep (Szymusiak, 2018; Te Lindert and Van Someren, 2018) and high nocturnal ambient temperatures have already been demonstrated to be followed by increased movements, more sleep interruptions, and reduced slow-wave and rapid-eye-movement sleep (Lohmus, 2018). Finally, a more psychological hypothesis is that the heat-induced effects on mental health they are mediated by violations of individual thermal comfort zones, which are between 15 °C and 26 °C outdoors (Potchter et al., 2018) and between 15 °C and 32.5 °C indoors (Arsad et al., 2023). Notably, these reactions may be amplified by appraisals of heat as a societal and/or individual threat, as manifested in climate anxiety (e.g., Bingley et al., 2022).

In concluding, it is worth mentioning that at both body core temperatures below 32.2 °C and above 37.7 °C, paradoxical effects have been observed with interventions powerful enough to decrease/increase body core temperature. Whole-body cryotherapy, a treatment during which the body is repeatedly exposed to temperatures between − 110 °C and − 195 °C and for several minutes has been found to reduce depressive symptoms. Therefore, although acute cold exerts negative effects on cognition and affect in the short-term, these may revert (in predisposed individuals) upon repeated exposure. Potential underlying mechanisms include increased behavioural activation, improved sleeping patterns as well as anti-inflammatory effects, as initially observed in patients with autoimmune disorders (Tabisz et al., 2023). Similarly, whole-body hyperthermia, a two-hour treatment during which ambient temperature is at approximately 57 °C, appears to exert antidepressant effects for up to six weeks. Interestingly, these effects are correlated with the extent to which specific inflammatory markers increase during heat application (Flux et al., 2023). Both findings are highly intriguing in light of the extant evidence for chronic low-grade inflammation in depressive disorders (Mac Giollabhui et al., 2021; Osimo et al., 2020; Wang and Miller, 2018) and may suggest that, at least in depressed individuals, repeated and/or high-intensity thermal challenges may influence biological pathways in a health-beneficial manner. They also highlight that psychological effects of temperature are highly dependent on exposure intensity, frequency and/or duration.

5. Discussion

The aim of this perspective article was to give a brief overview of the role of temperature in human cognition, affect, and behaviour, including implications for mental health. The most important temperature-related psychological effects are summarised in Fig. 3. As evident from the Figure, gaps in the literature in the lower body temperature range are vast and include basic knowledge about the effects of cold on affective/social functioning. In the normothermic range, effects of colder and warmer ambient temperature on social cognition are fairly robust, while effects on social behaviour remain equivocal. Gaps in the literature in the higher body temperature range are fewer and mainly include a lack of knowledge about the mechanisms translating warmth/heat into adverse psychological outcomes.

The presented research comes with a number of strengths and limitations, which bear important implications for future work in this emerging area. Regarding ambient temperature, a strength of the epidemiological studies is the almost consistent consideration of temperature confounding factors, such as climate zone, season, solar radiation, humidity, wind speed, and precipitation, with some studies incorporating thermal comfort indices in their analyses. By contrast, a limitation is the use of weather station data, which come with low spatial resolution and thus only represent a proxy of an individual's actual exposure to temperatures. Another limitation is the reliance on hospital records as a psychological outcome measure, with sub-clinical aspects of mental health, such as well-being, largely neglected, and with little evidence on the effects of ambient temperature on specific mental disorders (e.g., depressive disorders, anxiety disorders). While a strength of the experimental studies is the high degree of standardisation, little is still known about the differential impact of varying frequencies and durations of temperature exposure. Moreover, a limited set of (mostly cognitive) outcome variables has been employed in these studies. Regarding body temperature research, strengths of the clinical and experimental research include the relatively clear characterisation of the cognitive consequences of hypo- and hyperthermia. However, perhaps due to a former lack of reliable non-invasive methodology, barely any investigations into the psychological effects of smaller-scale changes in body core and skin temperature have, as of yet, been

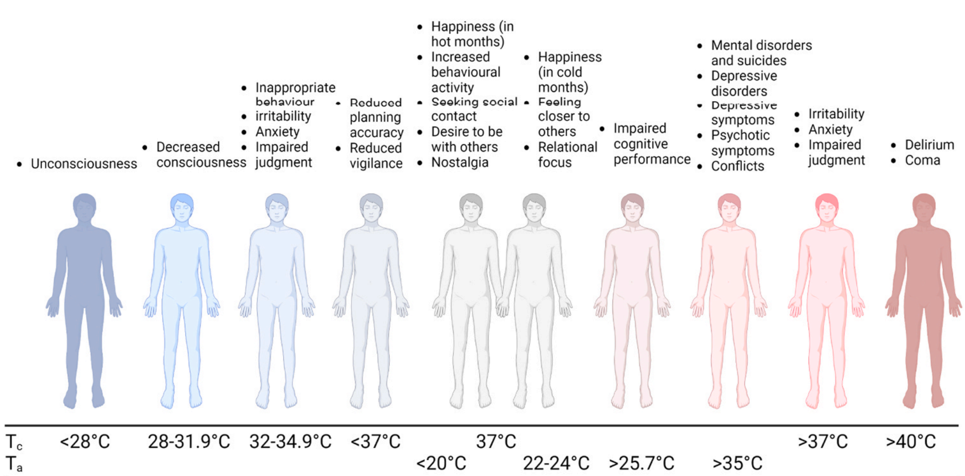

Fig. 3. Illustrated summary of the identified psychological effects of ambient/body temperature. T_a refers to ambient temperature and T_c refers to body core body temperature. Figure created with biorender.com.

undertaken. Finally, barely any research has integrated measures of ambient and body temperature, let alone complemented them with subjective measures (e.g., perceived temperature).

5.1. Outlook: basic research

It is clear from the above summary and limitations that more basic research into the psychological effects of ambient and body temperature is necessary. Given the projected increase in global warming, priority should be given to research into the psychological sequelae of warmth/heat. Ideally, such studies would see a (quasi-)experimental manipulation of ambient temperatures across different durations and intensities while continuously monitoring body temperature. The gold standard measure of body core temperature are brain, pulmonary artery, or temporal artery measures (Childs, 2018). However, with these methods being invasive, causing discomfort and, in rare cases, physical and/or mental harm, hope is now being placed on ingestible telemetric pills, which could, in the future, provide a safe and reliable alternative. Likewise, alongside conventional approaches, such as placing electrodes on the skin (e.g., the sternum), skin temperature can now be captured remotely by means of infrared thermal imaging (Cardone and Merla, 2017). Some of these methods are already implemented in wearables, which allow to extend research into more ecologically valid spaces, outside of the laboratory (see e.g., Dolson et al., 2022 for a review). Although the jury is still out on which of these devices are capable of reliable and valid temperature data collection, it is likely that this technology will become the gold standard in large-scale ecological momentary or ambulatory assessment studies.

As for outcomes, the Research Domain Criteria framework (RDoC) has systemised domains of functioning, which, according to this rubric, include arousal, cognition, valence, and social (Insel et al., 2010). As stated above, affective and social behavioural outcomes in particular have received little attention. At the same time, RDoC has highlighted the need to study biological mechanisms of interest, such as those translating heat into functional alterations, across multiple units of analysis (e.g., molecules, cells, neural circuits, physiology). Again, non-invasive methods, such as molecular analyses from dried blood spots (e.g., Fischer et al., 2019; Gardini et al., 2020) or hormonal analyses from saliva (Kirschbaum and Hellhammer, 1989) might prove helpful in delineating these mechanisms. As stated in the previous paragraph, it would be commendable if research would expand to include ecological momentary or ambulatory assessment study designs. By allowing to study relationships between temperature and biopsychological outcomes at high levels of spatial and temporal resolution and as they unfold in real life, such studies have the potential to bridge the gap between mechanistic evidence from laboratory-based experiments and population-based insights on health consequences.

One example for particulary promising basic research is the study by Inagaki and Human (2020), which sought to evaluate the relationship between body core temperature and social connectedness in people's daily lives. To this end, healthy adults provided repeated daily assessments of tympanic temperature and feelings of social connectedness over the course of one week. The authors found that real-time changes in body temperature predicted social connectedness, such that lower temperatures mapped onto lower feelings of connectedness and higher temperatures mapped onto greater connectedness. As technology advances, it is highly likely that this type of psychophysiological study will also be capable of providing insights into the mechanisms underlying these relationships as they unfold in everyday life.

5.2. Outlook: clinical research

As evident from the above summary and limitations, more clinical research into interventions which can modify temperature-induced effects on mental health is warranted. Given the projected increases in global near surface temperature and associated extreme weather events, environmental interventions targeting ambient heat have already begun to be developed. For instance, in urban outdoor spaces, the use of reflective surfaces (e.g., on roofs), vegetation, and water has been employed as a means to battle heat stress (Lai et al., 2019). Interestingly, there is evidence for humans to be able to adapt to increases in ambient temperature in the long term. For instance, when compared to people living in a temperate climate, tropical indigenous people appear to exhibit higher rectal temperatures and lower forehead skin temperatures, as well as great heat tolerance and cognitive performance under hot conditions (Tochihara et al., 2022). Nevertheless, for now, it is imperative that the designing of such interventions is mindful of the fact that vulnerable individuals, such as people of lower socioeconomic status, are more often exposed to extreme ambient temperatures (Evans, 2019). From a psychological point of view, behavioural changes in response to heat have recently become a focus of attention (Lim, 2020). For now, these measures include dressing for the weather, activity pacing, and hydration. However, it is conceivable that, in the future, more drastic measures will be adopted, which could range from portable body cooling systems to shifts into a sub-nocturnal lifestyle. Again, such interventions are and will be particularly crucial for vulnerable individuals, including children, older adults, pregnant people, individuals with pre-existing somatic diseases and mental disorders, and individuals taking medication, which are more frequently affected by deficits in thermoregulation (Evans, 2019).

Examples for particulary promising clinical research are summarised in a recent meta-analysis, which investigated the effects of so-called "nature prescriptions" on mental health (Nguyen et al., 2023). This analysis found that encouragements to spend time in green and blue spaces exerted positive cardiovascular effects and was efficacious in reducing symptoms of depression and anxiety. Therefore, such interventions not only have the potential to protect individuals from (urban) heat, but also to improve their mental health. The underlying mechanisms (as well as the answer to the question of whether such interventions may come with the additional benefit of increasing pro-environmental behaviour and mitigating climate change), however, remains to be determined by future psychophysiological research.

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Contributing authors

SF and UE conceived and designed the article. SF searched the literature. SF drafted the article and KN, DC, CF, AM, KH, and UE revised it critically for important intellectual content. All authors have approved the final article.

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No generative AI and AI-assisted technologies were used.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

None.

Data availability

No data was used for the research described in the article.

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