Physiology & Behavior 294 (2025) 114865

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Review

The psychology of thermoregulation: A coordinating mechanisms approach

Elias C. Acevedo [a,*], Kaitlyn P. White [b], Laith Al-Shawaf [b,c,d,e]

[a] University of California, Los Angeles, Department of Communication, 345 Portola Plaza, Los Angeles, CA 90095, USA
[b] University of Colorado, Colorado Springs, Department of Psychology, 1420 Austin Bluffs Pkwy, Colorado Springs, CO 80918, USA
[c] Lyda Hill Institute for Human Resilience, University of Colorado, Colorado Springs, USA
[d] Center for Cognitive Archaeology, University of Colorado, Colorado Springs, USA
[e] Institute for Advanced Study, Toulouse, France

ARTICLE INFO

Keywords:
Thermoregulation
Thermal comfort
Affect
Coordinating mechanisms
Task analysis
Cognition

ABSTRACT

Temperature is more than just the background setting of daily life—it shapes what we think, feel, and do. Drawing from the theory of emotions as coordinating mechanisms, we propose that thermal affect influences key psychological systems such as attention, memory, perception, and motivation in service of solving critical thermal challenges. Through an evolutionary task analysis, we generate a variety of testable predictions regarding the interplay of temperature, human cognition, and behavior. We hope that this manuscript contributes to the psychology of thermoregulation, a notably understudied area of research despite its importance to both basic and applied science.

1. The psychology of thermoregulation: A coordinating mechanisms approach

The ability to respond effectively to temperature fluctuations is essential for survival. Prior research has examined the effects of ambient temperature on cognitive performance (e.g., [1]), but much of this work focuses on temperature-irrelevant tasks, potentially overlooking the adaptive function of *thermal affect*—i.e., feeling hot or cold. We propose that thermal affect functions as a coordinating mechanism that strategically reallocates cognitive resources to address thermal challenges, prioritizing temperature-related problem-solving at the expense of unrelated tasks.

The theory of emotions as coordinating mechanisms [2–4] suggests that emotions are more than just "feelings"; they are vital regulators that coordinate various procedures in the body and mind to solve important problems. For example, fear helps evade danger, disgust defends against pathogens, and shame prevents social devaluation. This approach has advanced our understanding of emotions by specifying the adaptive functions that they serve and yielding a large bounty of new findings about how a variety of emotions work [5].

Through this lens, thermal affect can be viewed as a system that adjusts cognition, physiology, and behavior to manage thermal challenges. The coordinating mechanisms approach can be combined with the method of evolutionary task analysis ([3,6]; see also [7,8]) to generate novel, testable predictions about how thermal affect may influence cognition and behavior. Conducting a task analysis of thermoregulation involves asking the following key questions: What adaptive problem does thermal affect solve, if any? What subtasks must be solved in the overall problem of thermoregulation? Which cognitive processes are required to address these subtasks? Finally, how are these processes coordinated to deliver an effective response to the problem?

These questions have also been useful for understanding motivational states and drives that are not typically classified as emotions. Consider hunger. Through the lens of an evolutionary task analysis, hunger is a mechanism that coordinates physiology and psychology to address a fundamental problem—the need to acquire food [7]. Hunger appears to reorder our priorities and sharpen our attention to food-related cues, while also enhancing their appeal, making them more salient and more inviting. Hunger may also fine-tune our memory, making it easier to encode and recall where food can be found. In essence, hunger appears to function like an emotion in the sense that it orchestrates a multifaceted response, engaging multiple systems within the body and mind to better acquire food.

Like hunger, thermal affect is not typically categorized as an emotion, despite the state's valenced and motivational qualities [9]. Also like hunger, thermal affect is a crucial homeostatic process. In this paper, we suggest that thermal affect may coordinate physiology and psychology in line with that process. These considerations suggest that

* Corresponding author at: Department of Communication, University of California, Los Angeles, CA, 90095, USA.
E-mail address: eacevedo89@g.ucla.edu (E.C. Acevedo).

https://doi.org/10.1016/j.physbeh.2025.114865
Received 18 February 2024; Received in revised form 15 February 2025; Accepted 25 February 2025
Available online 26 February 2025

approaching thermal affect from a coordinating mechanisms perspective may yield new, testable hypotheses regarding its effects on cognition and behavior.

Here, we apply an evolutionary task analysis to thermal affect in order to generate new predictions about the psychology of thermoregulation. In doing so, we a) briefly review the physiological mechanisms of thermoregulation, b) outline the primary problems that must be solved to maintain thermal balance, c) highlight thermal affect's role in motivating behavior that addresses these challenges, d) identify certain cognitive processes that may contribute to solving these thermoregulatory problems, and e) generate new hypotheses about how thermal affect may influence cognition and behavior.

1.1. A brief summary of the physiology of thermoregulation

The human body is equipped with a sophisticated system for detecting and responding to temperature changes in order to maintain a stable core temperature in the face of external temperature shifts [9–11]. At the frontline of this system are peripheral sensors (i.e., thermoreceptors)—specialized nerve endings in the skin—that sense the temperature around us. These sensors use temperature-gated ion channels, proteins that allow charged ions to move through cell membranes [12]. Different channels respond to different temperature ranges, with some responding to heat, and others responding to cold [13]. When these channels are activated, they trigger signals that travel along the lateral spinothalamic tract to the hypothalamus. While these peripheral sensors monitor external temperatures, central sensors in the hypothalamus keep tabs on our core body temperature. These neurons detect shifts in blood temperature and receive additional information from receptors that populate the brainstem and other internal organs [14]. When the hypothalamus senses that the body is too hot or cold, it initiates a series of physiological responses to dissipate or generate heat [15].

The preoptic area of the hypothalamus triggers "thermoeffectors"—tissues and organs that help maintain thermal balance [11]. Blood vessels dilate (vasodilation) to release excess heat or constrict (vasoconstriction) to conserve heat. Sweat glands produce sweat, cooling the body through evaporation. Skeletal muscles shiver in response to the cold, producing rapid, involuntary contractions that generate heat. Brown adipose tissue generates heat through non-shivering thermogenesis. This process breaks down fat to produce heat instead of ATP, the cell's usual energy currency [16].

1.2. Adaptive problems of thermoregulation

If core temperature rises too much (hyperthermia), the body risks life-threatening cellular damage, dehydration, and heatstroke [17]. If core temperature drops too low (hypothermia), critical metabolic processes begin to slow down, leading to decreased consciousness, impaired motor function, and eventual organ failure and death [18]. Exposure to cold can also result in frostbite, which poses the risk of injury or death [19].

Thermoregulation also comes with additional challenges, such as energy expenditure. In cold environments, for instance, shivering demands substantial energy [20]. Given a finite budget of metabolic resources, when energy is devoted to maintaining thermal balance, less energy is available for other vital functions such as immune response, digestion, growth, repair, and reproduction [20,21]. This tradeoff has significant consequences for an organism's health, survival, and reproductive success.

For example, endotherms—organisms that generate their own internal heat, such as humans—often raise their body temperature in response to infection, inducing a fever [22]. Fever facilitates various immune functions, such as by mobilizing leukocytes, increasing the proliferation of T cells, and creating an environment that impedes the reproduction of pathogens [23]. But running a fever carries a high metabolic cost. To reduce this burden, organisms may seek out warmer microclimates, conserving energy by allowing the environment to help raise their body temperature. In humans, the "chills" experienced during illness appear to drive these warmth-seeking behaviors, enabling more energy to be allocated to immune responses [24].

Effective thermoregulation also depends on maintaining adequate levels of essential resources. Fluid and sodium lost through sweating, for example, must be replenished to avoid impairing the process of heat dissipation. Without enough water, the body's ability to sweat and cool down is compromised, and insufficient sodium intake increases the risk of heat exhaustion [25].

The thermal challenges described here—maintaining core body temperature, preventing thermal injuries like frostbite, meeting the metabolic demands of different bodily systems, and avoiding dehydration and nutrient depletion—are complex problems. Addressing these challenges requires a coordinated set of psychological, physiological, and behavioral responses to ensure survival Table 1.

1.3. Behavioral thermoregulation

Maintaining thermal balance is not just a matter of physiology; behavior also plays a crucial role [26]. The phenomenon of "behavioral thermoregulation" is widespread throughout the animal kingdom. For example, desert kangaroo rats escape the heat by burrowing and seeking out cooler microclimates during the day, which helps them conserve water and avoid overheating [27]. Dogs cool themselves through panting, a combined behavioral and physiological mechanism that dissipates heat by promoting water evaporation from the nose and lungs [28]. In response to infection, ectotherms—organisms that cannot internally regulate their body temperature—engage in "behavioral fever." For instance, a lizard might bask on a hot rock to elevate its body temperature, which aids in fighting off the infection ([29]; see also [30,31].

Social animals often employ collective strategies for thermoregulation. For example, emperor penguins huddle together in tightly packed groups to conserve heat, reducing the amount of body surface exposed to the cold and capitalizing on the warmth generated by their peers [32]. Honeybees regulate the temperature of their hive by fanning their wings to circulate air or clustering together to generate heat [33,34]. Some species of honeybee, like *Apis cerana* and *Apis mellifera*, even use behavioral thermoregulation as a defensive weapon; they form a "heat-ball" around invading hornets, raising their body temperatures along with the temperature inside the ball to a level that is lethal for the hornet, but not for the bees [35,36].

In humans, behavior driven by thermal affect is considered the *most* powerful form of thermoregulation [37]. In hot environments, people seek shade, drink more water, and slow down their activity to prevent

Table 1
Task analysis overview of thermal discomfort as a coordinating mechanism.

Adaptive problems	Subtasks	Information-processing programs	Program coordination
1. Maintaining core body temperature within a safe range 1a. Avoiding dehydration and nutrient depletion 2. Avoiding thermal injury 3. Meeting energetic demands	1. Seeking cooler/ warmer environments 2. Modifying activity, food, and fluid intake 4. Adjusting/ fashioning clothing 5. Seeking assistance from others	1. Attention 2. Perception 3. Memory and learning 4. Motivation	Details in Table 2

Note. This overview is meant as a starting point, not an exhaustive analysis. Future research will surely add additional adaptive problems and cognitive processes involved in thermoregulation.

overheating. In cold environments, people bundle up in warmer clothing, seek shelter, and increase physical activity to generate heat [9, 38,39].

The tendency for thermal affect to motivate behavioral adjustments is particularly evident when exercising. In hot environments, for example, human performance is significantly impaired as the body struggles to maintain a safe temperature [40–42]. Voluntary control of work rate and fluid intake becomes the first line of defense against overheating during physical exertion [39].

The key point is that thermal sensations and feelings adjust not only physiology (e.g., vasodilation and vasoconstriction), but also *behavior* (e.g., seeking shelter and adjusting activity levels) to maintain a stable core temperature, optimize energy use, and prevent injury or death. Despite its significance, the psychology of thermoregulation remains surprisingly understudied, making it a rich area for future research.

2. Possible effects of thermal affect on cognition

How do thermal challenges shape our thinking? The idea that extreme temperatures tend to impair cognition is well-established [43]. However, much of this research has focused on ecologically irrelevant tasks that do not reflect real-world thermal challenges, such as math problems [1]. These measures potentially overlook the strategic reallocation of cognitive resources toward alleviating thermal discomfort. It is therefore possible that many of the detrimental effects of hot and cold environments on cognition reflect, at least in part, shifting priorities rather than generalized impairments. Failure to consider this adaptive cognitive shift may lead to an inflated perception of impairment.

Previous work suggests hunger may employ a similar prioritization scheme, leading to a decrement in most problem-solving domains but simultaneously enhancing problem-solving when it pertains to food acquisition [7]. Just as hunger orients the mind toward finding food, thermal affect may channel cognitive resources toward solving the immediate thermal problem. If this is correct, this reallocation of mental resources should enhance problem-solving in domains relevant to the thermal challenge, while other, less critical tasks take a back seat and may experience a decrement in performance.

Below, we review existing research on how temperature influences various cognitive processes. In doing so, we examine how thermal affect might influence certain cognitive abilities, such as attention and memory, to meet the thermal challenges we face. We make several predictions along the way that we hope might open new avenues for future research on the psychology of thermoregulation.

2.1. Attention and problem solving

2.1.1. Existing research

How does thermal affect shape our focus? Moderate exposure to cold and heat has been found to both sharpen and dull attention, depending on the context [44,45]. However, when the cold becomes extreme enough to lower core body temperature, the detrimental impact on attention is consistent and severe [20,45]. The short-term cognitive improvements observed in some studies may be partly attributable to the acceleration of enzymatic processes under heat stress, temporarily enhancing reaction speed [46,47]. Prolonged exposure, however, leads to reduced cerebral blood flow due to hyperventilation, which, coupled with the body's increasing energy demands to maintain core temperature, ultimately results in cognitive fatigue and impaired attention [48].

Two existing theories attempt to explain the effects of cold environments on attention, each of which emphasizes a different proximate mechanism. The *distraction hypothesis* suggests that thermal discomfort draws attentional resources away from primary tasks, leading to poorer performance on attention-demanding activities [20,45]. In contrast, the *arousal hypothesis* suggests that moderate cold exposure can initially enhance cognitive performance by boosting overall arousal, but this benefit is short-lived, giving way to cognitive decline as the cold persists or intensifies [20].

2.1.2. Novel predictions

The idea that hot and cold environments often have a detrimental effect on attention prompts the question: attention *to what, exactly*? We propose that thermal affect may temporarily reallocate attentional resources to alleviate the problem of thermal discomfort. When facing thermal stress, our cognitive system may sharpen focus on temperature-related information and resources—those that can help us warm up in the cold or cool down in the heat. Heightened attention to thermally relevant cues would come at the expense of other, less critical tasks. This adaptive shift in attention may explain why performance on standard lab tasks, like the Stroop test (e.g., [49]), often decreases under thermal stress—these tasks become secondary as the brain prioritizes other tasks to relieve thermal discomfort.

The extent to which thermal affect distracts attention from other fitness-relevant problems or opportunities should depend on the intensity of thermal affect—which indexes the degree of thermal threat—relative to other problems that need solving. For instance, moderate thermal discomfort might divert attention away from a mild pathogen threat—which typically elicits disgust and avoidance behaviors—but not from a more severe one, whereas extreme thermal discomfort might override attention to both. Understanding how organisms prioritize between competing adaptive problems can lead to specific, testable predictions about how thermal affect operates in various contexts (e.g., [7]).

The costs and benefits of focusing on one issue over another would have significantly varied throughout human evolution, depending on the context and the individual. This suggests that solutions to competing problems are not one-size-fits-all; they are systematically tailored to the circumstance ([7]; see also [50]). For example, children face greater challenges in retaining and dissipating heat compared to adults, given their distinct morphology (e.g., a larger surface-to-mass ratio) and physiology (e.g., reduced sweat rate) [51,52]. As such, we might expect the effects of thermal affect on cognition to be more pronounced in children, with temperature-relevant cues more powerfully influencing children's attention relative to adults.

In essence, thermal affect may adaptively reallocate attentional resources toward solving the specific thermal challenges we face, ensuring that we remain focused on the goal of maintaining thermal balance. If correct, this would result in enhanced thermal problem solving[1] but simultaneously decrease problem-solving performance in other domains.

2.2. Perception

2.2.1. Existing research

How does thermal affect shape the way we perceive the world? Existing research suggests that thermal affect fine-tunes perception to meet the body's needs. For instance, whether we find the temperature pleasant or unpleasant is anchored to our body's internal state [53,54]. When overheated, a cool breeze or a sip of cold water feels refreshing. But the same cold water feels uncomfortable or even painful when we are already chilled.

This perceptual tuning is adaptive, as it enables our sensory experiences to guide us toward environments and actions that maintain our body's optimal temperature [9]. For example, exercising in the heat increases perceptions of effort and strain, prompting reduced activity in order to conserve energy and prevent overheating [39]. Hot environments have also been shown to decrease appetite, especially of protein-rich foods – this too, is adaptive, as protein-rich foods generate

[1] Only during conditions of mild or possibly moderate thermal discomfort. As noted earlier, extreme temperatures and extreme thermal discomfort is known to inhibit performance.

more metabolic heat. Decreased appetite in hot environments therefore effectively reduces the amount of heat produced through digestion [25]. Existing research suggests that even our taste preferences can shift in response to thermal stress. Extreme sodium depletion, which can be caused by excessive sweating, has been shown to make salty foods more appealing. This helps us to replenish a nutrient that is vital for maintaining thermal balance in the heat [55].

2.2.2. Novel predictions

One way that perceptual mechanisms may help solve thermal problems is by increasing the salience of temperature-relevant information by adjusting detection thresholds and increasing sensitivity to stimuli that offer thermal relief. For example, we might expect feeling too hot to improve the perceptual encoding of visual stimuli that indicate a source of shade, given that resting in the shade is a common means of behavioral thermoregulation in humans and non-human animals [56]. This enhanced encoding could occur through a mechanism that increases the perceived contrast of darkness (a quality of a shadow) in the surrounding environment, thereby facilitating the detection of distant shaded areas. The valence of perceived stimuli may also change – for example, hot sensations may also increase the appeal of visual stimuli that have cooling properties (e.g., shade or water), whereas cold sensations may increase the appeal of stimuli that can be used to warm oneself (e.g., enclosed spaces, blankets, clothing, or fire).

These hypotheses are preliminary and should be regarded as tentative until they are tested, but they are not without precedence. For example, some evidence suggests that hunger exerts a similar effect on visual perception, such that people who are hungry perceive food to be brighter than people who are satiated [57]. Existing research also shows that thirst increases the cognitive accessibility of drinking-related stimuli [58] and that thirsty people more readily perceive transparency (a quality of water) in ambiguous stimuli [59].

2.3. Memory and learning

2.3.1. Existing research

How does temperature shape what we remember or learn? Cold exposure is often associated with impairments in memory encoding and recall (e.g., [45]). The effects of heat on memory are less clear, with studies producing mixed results [44]. The challenge in these studies often lies in teasing apart the direct impact of temperature from other factors like physical exertion, which can also influence cognitive performance (e.g., [60,61,62]).

Existing research leaves several questions unanswered. For example, could thermal affect play an adaptive role in regulating memory and learning, guiding us to better remember temperature-relevant information that is critical to our survival? To the best of our knowledge, no research has directly tested this possibility.

2.3.2. Novel predictions

We propose that thermal affect may play a role in enhancing the memory encoding and retrieval of temperature-related information. For example, thermal affect may enhance our ability to remember which behaviors were most effective in alleviating thermal discomfort in previous situations, such as where shelter was found during a previous cold spell, or where water was found during a previous drought. As with the proposed effects of thermal affect on attention, this process is expected to impair the memory encoding and recall of information that is irrelevant to the problem at hand.

This memory function aligns with the broader phenomenon of acclimation. Acclimation involves a wide range of physiological and behavioral adjustments [20,63] that improve the body's ability to handle temperature fluctuations through repeated exposure. Over time, acclimation leads to better tolerance and performance in hot and cold environments, reducing the risk of heat- or cold-related illnesses [20,38, 56]. Part of this acclimation process may conceivably be driven by enhanced memory encoding and retrieval of temperature-related information. As individuals repeatedly face thermal challenges, their memories of effective strategies and resources may become more accessible, facilitating more effective behavioral thermoregulation over time.

2.4. Motivation

2.4.1. Existing research

Thermal affect is a powerful motivator. Existing research shows that when we feel too hot or cold, our primary motivation shifts toward actions that can restore thermal comfort [9,11,63,64]. Whether it's seeking shade on a sweltering day or huddling close to a fire in the cold, thermal affect drives behavior in ways that facilitate thermoregulation. What remains less understood is how thermal affect interacts with other needs and motivations. For instance, when alleviating thermal discomfort conflicts with the need for food, social interaction, or safety, how do we decide which goal to pursue?

2.4.2. Novel predictions

Depending on the intensity of the discomfort and the context at hand, the drive to alleviate thermal discomfort can be so powerful that it overshadows other competing motivations. By considering the degree of threat posed by the thermal discomfort and weighing it against the potential benefits of other behaviors, researchers can generate predictions about which motivations will take precedence, which should vary based on factors such as context, sex, and individual differences.

For instance, in a scenario where the need to reduce thermal discomfort conflicts with avoiding potential pathogen exposure, the behavior that ultimately prevails will likely depend on several factors. These include the intensity of the thermal affect, which reflects the severity of the thermal threat, and the perceived risk of the pathogen threat [65]. Additionally, individuals with higher disgust sensitivity, which is linked to pathogen avoidance, may be more likely to prioritize avoiding pathogen threats (e.g., [66]).

In this framework, thermal affect is expected to downregulate motivations that conflict with thermoregulatory goals and amplify those that promote restoring thermal balance. For example, behaviors like migrating or seeking shelter—key forms of behavioral thermoregulation [39,56,63]—might require venturing into unfamiliar or even dangerous environments in search of resources that can alleviate thermal discomfort. In such cases, thermal affect may temporarily suppress fear and boost exploratory behavior to achieve thermoregulatory goals.

However, this adaptive shift is likely to vary depending on the intensity and duration of the thermal discomfort. For instance, in cases of extreme or prolonged thermal discomfort, the body's need to conserve energy might become paramount, leading to a reduction in physical activity. This shift could manifest as a suppression of exploratory motivations, favoring more energy-efficient strategies to manage thermal stress. The dynamic nature of these responses highlights the flexibility of our motivational systems, allowing them to prioritize different goals based on the immediate context and the broader array of competing adaptive challenges. Despite the widespread misconception, an evolutionary approach to motivation and emotion does *not* imply rigidity or inflexibility (e.g., see [50]) (Table 2).

3. Conclusion

The theory of emotions as coordinating mechanisms [3,4,29,67] offers a generative explanatory and predictive framework for understanding how emotions tune our minds and bodies toward solving specific adaptive challenges. Among these challenges, thermoregulation stands out as a critical homeostatic process, essential for maintaining optimal body temperature to ensure survival in diverse and often harsh environments. Despite its undeniable significance—often a matter of life or death—thermoregulation has remained an underexplored area in the

Table 2
Some testable predictions yielded by a task analysis of thermal affect.

Attention	Perception	Memory and learning	Motivation
1. Increased attention to and performance on temperature-relevant information and tasks 2. Decreased attention to and performance on temperature-irrelevant information and tasks 3. Context-sensitive tradeoffs in attentional resources that conflict with other adaptive problems	1. Increased salience of stimuli with heating or cooling properties 2. Increased discrimination of stimuli with heating or cooling properties 3. Increased preference for stimuli with heating or cooling properties	1. Increased encoding and recall of temperature-relevant information 2. Decreased encoding and recall of temperature-irrelevant information 3. Mediation of temperature acclimation through repeat exposure	1. Increased motivation toward thermoregulatory goals 2. Decreased motivation toward non-thermoregulatory goals 3. Context-sensitive reordering of motivational priorities

psychological sciences.

Here, we have proposed that thermal affect may function as a coordinating mechanism, orchestrating various aspects of psychology, physiology, and behavior to carry out the tasks involved in maintaining thermal balance. To examine this hypothesis, we applied an evolutionary task analysis ([6]; see also [7,3]) to thermal affect, outlining the primary adaptive problems related to thermoregulation and generating testable predictions about the ways that thermal affect might affect cognition.

Our analysis is intended as a starting point rather than a comprehensive framework. We hope it opens the door to new research into the psychology of thermoregulation. Future research should aim to incorporate more ecologically valid tasks—i.e., tasks comprised of temperature-relevant information that can be used to solve thermal challenges—to distinguish between performance enhancement or impairment in temperature-relevant vs. irrelevant tasks. To examine the impact of thermal affect on memory, for example, researchers can create conditions of thermal comfort and thermal *dis*comfort, then test participants' encoding and recall of temperature-relevant and irrelevant stimuli, such as a shaded tree versus a neutral object like a pencil. Similarly, researchers can examine the effects of thermal discomfort on perception by presenting participants with temperature-related (e.g., a fire) and unrelated stimuli and measuring their preferences, accuracy, and sensitivity across multiple sensory domains.

We stress again that these ideas are preliminary, but we hope that they might serve as a launchpad for greater interest in and research on the psychology of thermoregulation, a critical but understudied homeostatic process in the cognitive and behavioral sciences.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sector.

CRediT authorship contribution statement

Elias C. Acevedo: Conceptualization, Writing – original draft, Writing – review & editing. **Kaitlyn P. White:** Conceptualization, Writing – review & editing. **Laith Al-Shawaf:** Writing – review & editing.

Declaration of competing interest

None.

Acknowledgements

The authors thank Joe Alcock and Nathan Morris for their helpful comments on an earlier draft of this paper.

References

[1] A.J. Yeganeh, G. Reichard, A.P. McCoy, T. Bulbul, F. Jazizadeh, Correlation of ambient air temperature and cognitive performance: a systematic review and meta-analysis, Build. Environ. 143 (2018) 701–716, https://doi.org/10.1016/j.buildenv.2018.07.002.

[2] L. Cosmides, J. Tooby, Evolutionary psychology and the emotions, in: M. Lewis, J. M. Haviland-Jones (Eds.), Handbook of Emotions, 2nd ed., Guilford, New York, 2000, pp. 91–115.

[3] J. Tooby, L. Cosmides, The past explains the present: emotional adaptations and the structure of ancestral environments, Ethol. Sociobiol. 11 (1990) 375–424.

[4] J. Tooby, L. Cosmides, The evolutionary psychology of the emotions and their relationship to internal regulatory variables, in: M. Lewis, J.M. Haviland-Jones, L. F. Barrett (Eds.), Handbook of Emotions, 3rd ed., Guilford, New York, 2008, pp. 114–137.

[5] L. Al-Shawaf, T.K. Shackelford, The oxford handbook of evolution and the emotions, Oxford University Press, Oxford, 2024.

[6] D. Marr, Vision: A computational Investigation Into the Human Representation and Processing of Visual Information, Freeman, San Francisco, 1982.

[7] L. Al-Shawaf, The evolutionary psychology of hunger, Appetite 105 (2016) 591–595.

[8] D.M.G. Lewis, L. Al-Shawaf, D. Conroy-Beam, K. Asao, D.M. Buss, Evolutionary psychology: a how-to guide, Am. Psychol. 72 (4) (2017) 353.

[9] A.D. Craig, How do you feel? Interoception: the sense of the physiological condition of the body, Nat. Rev. Neurosci. 3 (8) (2002) 655–666, https://doi.org/10.1038/nrn894.

[10] A.A. Romanovsky, Thermoregulation: some concepts have changed. Functional architecture of the thermoregulatory system, Am. J. Physiol. Regul. Integr. Comp. Physiol. 292 (1) (2007) 37–46, https://doi.org/10.1152/ajpregu.00668.2006.

[11] Z.J. Schlader, N.T. Vargas, Regulation of body temperature by autonomic and behavioral thermoeffectors, Exerc. Sport Sci. Rev. 47 (2) (2019) 116–126, https://doi.org/10.1249/JES.0000000000000180.

[12] A. Patapoutian, A.M. Peier, G.M. Story, V. Viswanath, ThermoTRP channels and beyond: mechanisms of temperature sensation, Nat. Rev. Neurosci. 4 (7) (2003) 529–539, https://doi.org/10.1038/nrn1141.

[13] J. Vriens, B. Nilius, T. Voets, Peripheral thermosensation in mammals, Nat. Rev. Neurosci. 15 (9) (2004) 573–589, https://doi.org/10.1038/nrn3784.

[14] N.B. Morris, D. Filingeri, M. Halaki, O. Jay, Evidence of viscerally-mediated cold-defence thermoeffector responses in man, J. Physiol. 595 (4) (2017) 1201–1212, https://doi.org/10.1113/JP273052.

[15] A.S. Milton, Thermal physiology: brief history and perspectives, in: C.M. Blatteis (Ed.), Physiology and Pathophysiology of Temperature Regulation, World Scientific, Singapore, 1998, pp. 3–12.

[16] D.P. Blondin, F. Haman, Shivering and nonshivering thermogenesis in skeletal muscles, Handb. Clin. Neurol. 156 (2018) 153–173.

[17] L.R. Leon, B.G. Helwig, Heat stroke: role of the systemic inflammatory response, J. Appl. Physiol. 109 (6) (2010) 1980–1988, https://doi.org/10.1152/japplphysiol.00301.2010.

[18] D.J.A. Brown, H. Brugger, J. Boyd, P. Paal, Accidental hypothermia, N. Engl. J. Med. 367 (20) (2012) 1930–1938, https://doi.org/10.1056/NEJMra1114208.

[19] J.V. Murphy, P.E. Banwell, A.H. Roberts, D.A. McGrouther, Frostbite: pathogenesis and treatment, J. Trauma Acute Care Surg. 48 (1) (2000) 171.

[20] T.M. Mäkinen, Different types of cold adaptation in humans, Front. Biosci. (2010).

[21] J.E. Silva, Thermogenic mechanisms and their hormonal regulation, Physiol. Rev. 86 (2) (2006) 435–464, https://doi.org/10.1152/physrev.00009.2005.

[22] M.J. Kluger, D.H. Ringler, M.R. Anver, Fever and survival, Science (1979) 188 (4184) (1975) 166–168. http://www.jstor.org/stable/1739904.

[23] M.P. Fischler, W.H. Reinhart, Fieber: freund oder feind? [Fever: friend or enemy?], Schweiz. Med. Wochenschr. 127 (20) (1997) 864–870.

[24] J.M. Schrock, J.J. Snodgrass, L.S. Sugiyama, Lassitude: the emotion of being sick, Evol. Hum. Behav. 41 (1) (2020) 44–57, https://doi.org/10.1016/j.evolhumbehav.2019.09.002.

[25] Marriott, B.M. (Ed.). (1993). Nutritional needs in hot environments: applications for military personnel in field operations.

[26] M. Cabanac, Heat stress and behavior, in: M.J. Fregley, C.M. Blatteis (Eds.), Handbook of Physiology, Section 4: Environmental Physiology, Oxford University Press, New York, 1996, pp. 261–278.

[27] M. Banta, Merriam's kangaroo rats (dipodomys merriami) voluntarily select temperatures that conserve energy rather than water, Physiol. Biochem. Zool. 76 (4) (2003) 522–532, https://doi.org/10.1086/375437.

[28] J. Terrien, M. Perret, F. Aujard, Behavioral thermoregulation in mammals: a review, Front. Biosci. 16 (4) (2011) 1428–1444.

[29] K. Rakus, M. Ronsmans, A. Vanderplasschen, Behavioral fever in ectothermic vertebrates, Dev. Comp. Immunol. 66 (2017) 84–91, https://doi.org/10.1016/j.dci.2016.06.027.

[30] L. Al-Shawaf, Why do we get sick? The new science of evolutionary medicine, Areo (2023). https://areomagazine.com/2023/08/23/why-do-we-get-sick-the-new-science-of-evolutionary-medicine/.

[31] R.M. Nesse, G.C. Williams, Why we get sick: the new science of darwinian medicine, Vintage, 2012.

[32] A. Ancel, C. Gilbert, N. Poulin, M. Beaulieu, B. Thierry, New insights into the huddling dynamics of emperor penguins, Anim. Behav. 110 (2015) 91–98, https://doi.org/10.1016/j.anbehav.2015.09.019.

[33] T.D. Seeley, The wisdom of the hive: the social physiology of honey bee colonies, Harvard University Press, 1995.

[34] E.E. Southwick, The honey bee cluster as a homeothermic superorganism, Comp. Biochem. Physiol. Part A: Physiol. 75 (4) (1983) 641–645, https://doi.org/10.1016/0300-9629(83)90434-6.

[35] T. Ken, H.R. Hepburn, S.E. Radloff, Y. Yusheng, L. Yiqiu, Z. Danyin, P. Neumann, Heat-balling wasps by honeybees, Naturwissenschaften. 92 (10) (2005) 492–495, https://doi.org/10.1007/s00114-005-0026-5.

[36] T. Ken, M. Yang, Z. Wang, H. Li, Z. Zhang, S.E. Radloff, R. Hepburn, Cooperative wasp-killing by mixed-species colonies of honeybees, apis cerana and apis mellifera, Apidologie 43 (2) (2012) 195–200, https://doi.org/10.1007/s13592-011-0098-5.

[37] J.D. Hardy, Thermal comfort and health, ASHRAe J. 13 (1971) 43–51.

[38] J.W. Castellani, A.J. Young, Human physiological responses to cold exposure: acute responses and acclimatization to prolonged exposure, Auton. Neurosci. 196 (2016) 63–74, https://doi.org/10.1016/j.autneu.2016.02.009.

[39] A.D. Flouris, Z.J. Schlader, Human behavioral thermoregulation during exercise in the heat, Scand. J. Med. Sci. Sports 25 (S1) (2015) 52–64, https://doi.org/10.1111/sms.12349.

[40] S.S. Cheung, G.G. Sleivert, Multiple triggers for hyperthermic fatigue and exhaustion, Exerc. Sport Sci. Rev. 32 (3) (2004) 100–106, https://doi.org/10.1097/00003677-200407000-00005.

[41] B. Nielson, L. Nybo, Cerebral changes during exercise in the heat, Sports Med. (Auckland) 33 (1) (2003) 1–11, https://doi.org/10.2165/00007256-200333010-00001.

[42] L. Nybo, P. Rasmussen, M.N. Sawka, Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue, Compr. Physiol. 4 (2) (2014) 657, https://doi.org/10.1002/cphy.c130012.

[43] J.J. Pilcher, E. Nadler, C. Busch, Effects of hot and cold temperature exposure on performance: a meta-analytic review, Ergonomics 45 (10) (2002) 682–698, https://doi.org/10.1080/00140130210158419.

[44] R.A. Malcolm, S. Cooper, J.P. Folland, C.J. Tyler, C. Sunderland, Passive heat exposure alters perception and executive function, Front. Physiol. 9 (2018) 585, https://doi.org/10.3389/fphys.2018.00585.

[45] L.A. Palinkas, Mental and cognitive performance in the cold, International Journal of Circumpolar Health 60 (3) (2001) 430–439.

[46] L. Nybo, CNS fatigue provoked by prolonged exercise in the heat, Front. Biosci. (Elite Ed.) 2 (2) (2010) 779–792.

[47] J.F. Piil, L. Christiansen, N.B. Morris, C.J. Mikkelsen, L. Nybo, Direct exposure of the head to solar heat radiation impairs motor-cognitive performance, Sci. Rep. 10 (1) (2020) 9442, https://doi.org/10.1038/s41598-020-64768-w.

[48] L. Nybo, Hyperthermia and fatigue, J. Appl. Physiol. 104 (3) (2008) 871–878, https://doi.org/10.1152/japplphysiol.00910.2007.

[49] A. Jonsson, S. Hedman, Moderately cold indoor temperatures' effect on human attention: immediate decrease in inhibiting erroneous responses. (Unpublished Bachelor's Thesis), Umeå University, Sweden, 2018.

[50] L. Al-Shawaf, D.M. Lewis, Y.S. Wehbe, D.M. Buss, Context, environment, and learning in evolutionary psychology. Encyclopedia of evolutionary psychological science, Springer International Publishing, Cham, 2019, pp. 1330–1341.

[51] N. Ravanelli, N. Morris, S.A. Morrison, 24-h movement behaviour, thermal perception, thirst, and heat management strategies of children and adults during heat alerts: a pilot study, Front. Physiol. 14 (2023) 1179844.

[52] C.J. Smith, Pediatric thermoregulation: considerations in the face of global climate change, Nutrients. 11 (9) (2019) 2010.

[53] M. Cabanac, B. Massonnet, R. Belaiche, Preferred skin temperature as a function of internal and mean skin temperature, J. Appl. Physiol. 33 (6) (1972) 699–703.

[54] G.D. Mower, Perceived intensity of peripheral thermal stimuli is independent of internal body temperature, J. Comp. Physiol. Psychol. 90 (12) (1976) 1152–1155, https://doi.org/10.1037/h0077284.

[55] G.K. Beauchamp, M. Bertino, D. Burke, K. Engelman, Experimental sodium depletion and salt taste in normal human volunteers, Am. J. Clin. Nutr. 51 (5) (1990) 881–889.

[56] J.D. Périard, S. Racinais, M.N. Sawka, Adaptations and mechanisms of human heat acclimation: applications for competitive athletes and sports: adaptations and mechanisms of heat acclimation, Scand. J. Med. Sci. Sports 25 (2015) 20–38, https://doi.org/10.1111/sms.12408.

[57] J.C. Gilchrist, L.S. Nesberg, Need and perceptual change in need-related objects, J. Exp. Psychol. 44 (6) (1952) 369.

[58] H. Aarts, A. Dijksterhuis, P. De Vries, On the psychology of drinking: being thirsty and perceptually ready, Br. J. Psychol. 92 (4) (2001) 631–642.

[59] M.A. Changizi, W.G. Hall, Thirst modulates a perception, Perception. 30 (12) (2001) 1489–1497.

[60] S. Bandelow, R. Maughan, S. Shirreffs, K. Ozgünen, S. Kurdak, G. Ersöz, et al., The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. *Scand*, J. Med. Sci. Sports 20 (2010) 148–160, https://doi.org/10.1111/j.1600-0838.2010.01220.x.

[61] J.K. Lee, A.C. Koh, S.X. Koh, G.J. Liu, A.Q. Nio, P.W. Fan, et al., Neck cooling and cognitive performance following exercise-induced hyperthermia, Eur. J. Appl. Physiol. 114 (2014) 375–384, https://doi.org/10.1007/s00421-013-2774-9.

[62] H.R. Lieberman, G.P. Bathalon, C.M. Falco, F.M. Kramer, C.A. Morgan, P. Niro, et al., Severe decrements in cognition function and mood induced by sleep loss, heat, dehydration, and undernutrition during simulated combat, Biol. Psychiatry 57 (2005) 422–429, https://doi.org/10.1016/j.biopsych.2004.11.014.

[63] J. Lind, An Essay On Diseases Incidental to Europeans. *Hot climates: With the Method of Preventing Their Fatal Consequences*, Becket De Hondt, London, 1768, pp. 1–348.

[64] E. Satinoff, Neural organization and evolution of thermal regulation in mammals, Sci. (Am. Assoc. Adv. Sci.) 201 (4350) (1978) 16–22, https://doi.org/10.1126/science.351802.

[65] White, K.P., Acevedo, E., Lewis, D.M.G., Al-Shawaf, L. (2025). Disgust systematically tracks relative level of pathogen threat, not just absence or presence of pathogens. *Motivation and Emotion*.

[66] L. Al-Shawaf, D.M.G. Lewis, M.E. Ghossainy, D.M. Buss, Experimentally inducing disgust reduces desire for short-term mating, Evol. Psychol. Sci. 5 (3) (2019) 267–275, https://doi.org/10.1007/s40806-018-0179-z.

[67] L. Al-Shawaf, D. Conroy-Beam, K. Asao, D.M. Buss, Human emotions: an evolutionary psychological perspective, Emot. Rev. (2016) 1–14.