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Neural adaptation to climate change: mechanisms, limits and opportunities

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Rising environmental temperatures challenge nervous systems. We examine how neural systems enable acclimation to prolonged heat exposure, the limits of such adaptation, and the behavioural and social strategies that shape heat resilience. Understanding the neural mechanisms of adaptation to heat may inform strategies to cope with a warming world.

Temperature shapes nervous-system function by influencing the molecular and biophysical processes that underlie neuronal signalling and network activity. Even small temperature shifts modify action-potential waveforms, neurotransmitter release probability and neuronal excitability. Mammals counter these intrinsic thermal sensitivities through a hierarchical thermoregulatory system in which peripheral thermoreceptors, spinal pathways and hypothalamic networks regulate and stabilize core temperature[1]. At the same time, neural circuits display robust output across wide temperature ranges through coordinated adjustments in ion-channel conductances[2].

These mechanisms enable stable function to emerge from inherently temperature-sensitive components. However, this robustness is not unlimited: when temperature changes become too steep, too prolonged or exceed compensatory bounds, circuit dynamics destabilize. As climate change pushes global temperatures upwards, organisms will increasingly depend on additional autonomic, metabolic and behavioural adjustments. Understanding the neural mechanisms that drive these adaptations, their plasticity and their limits may provide insights into strategies to bolster climate resilience.

Neural mechanisms of heat acclimation

Although short-term circuit compensation preserves neural function through homeostatic buffering of acute thermal perturbations, long-term heat exposure requires rheostatic reconfiguration of autonomic and behavioural control systems. This process, known as heat acclimation, entails a coordinated, reversible resetting of physiological and behavioural operating points that increases heat tolerance. Heat-acclimation-associated adaptive changes observed in humans and model organisms include reductions in heart rate, decreased food intake (accompanied by loss of body mass), reduced energy expenditure and suppression of thermogenic processes such as brown adipose tissue activity[3,4]. Together, these changes reduce endogenous heat production and facilitate heat dissipation, and thereby stabilize core body temperature (T_{core}). In parallel, sustained heat exposure reshapes behaviour: for example, rodents reduce ambulatory activity, modify nest-building strategies, adopt heat-dissipating postures and limit social interactions to lower the thermal burden[4]. These autonomic and behavioural adjustments allow organisms to maintain stable physiological performance in hot environments.

The neuronal mechanisms that orchestrate heat acclimation have only recently begun to emerge, with the hypothalamic thermoregulatory centre — which includes the preoptic area (POA) — being implicated in mediating autonomic adaptations to prolonged heat exposure. Hypothalamic heat shock responses, epigenetic changes and changes in neuronal excitability have been implicated in heat acclimation[5]. Recent studies describe durable changes in the activity and responsiveness of defined POA neuronal populations that parallel, and probably drive, organ-level adaptations that enhance heat tolerance[6,7].

Although extreme heat exacerbates multiple pathological conditions (including neurological disorders), controlled heat acclimation has been proposed to beneficially modify cardiovascular function[8]. An unresolved question is therefore whether the neural circuits that drive heat acclimation can be selectively engaged or modulated to promote beneficial adaptations, while minimizing maladaptive outcomes. To answer this question, we will require a better understanding of these circuits and of the slowly evolving neuronal plasticity mechanisms that appear to drive autonomic (and possibly behavioural) adaptations to prolonged heat exposure.

Neural regulation of heat exposure

Ultimately, the autonomic and peripheral adaptations involved in heat acclimation probably have hard physiological limits. Indeed, when heat exposure becomes too intense, too prolonged or too rapidly escalating, these compensatory mechanisms can become overwhelmed. The greatest remaining adaptive potential may therefore lie in the higher-order behavioural and cognitive strategies that shape human heat exposure, including thermomobility and thermal agency (Fig. 1). Understanding the neural adaptations that mediate these strategies is therefore important for developing approaches to mitigate the consequences of heat in a warming world.

The concept of thermal comfort (feeling neither too warm nor too cold) has been widely used in human studies to capture the subjective effects of environmental temperature, and is a key driver of the behaviours that humans deploy to control heat exposure. Gaining an improved neuromechanistic understanding of the experience of thermal comfort is therefore an important focus for climate-change-related neuroscience. However, this research faces several challenges, including the large differences between individuals in subjective comfort at a given ambient temperature, and variation with state factors such as clothing, activity levels and time of day. Most studies use simple rating scales to measure perceived thermal comfort, but these methods can conflate perceptual sensitivity with non-perceptual biases. Studies using psychophysical methods, such as perceptual discrimination between pairs of environmental temperatures, would therefore be valuable. Neuroimaging studies could also identify the neural bases of

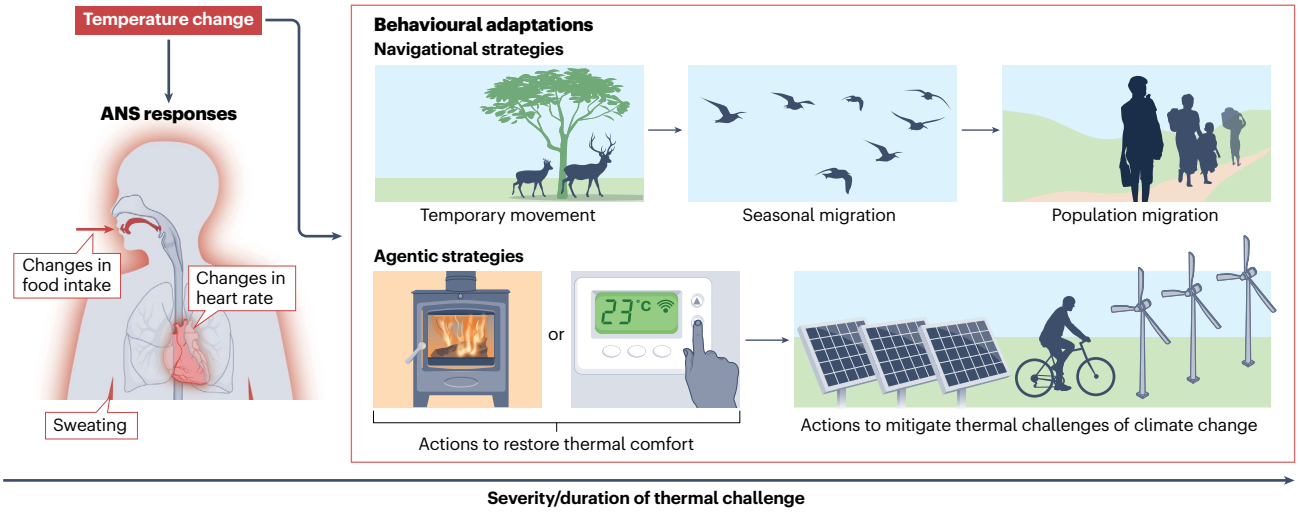

Fig. 1 | Cascading neural responses to thermal challenges. Animals, including humans, adapt to increasing thermal challenges in several ways. The autonomic nervous system (ANS) provides ongoing homeostatic compensation for short-term challenges and can shift homeostatic set points in response to long-term thermal challenges (rheostasis). In parallel to autonomic responses, animals also engage behavioural thermoregulation – for example, temporarily moving into shaded areas to reduce heat exposure. More severe and long-lasting challenges trigger cascades of rheostatic responses that include two broad classes of progressive behavioural adaptations. In navigational adaptation, animals and humans may move temporarily or permanently to find more comfortable thermal environments. In agentic adaptation, animals – and particularly humans – act on the environment itself to increase thermal comfort. This may include both actions that rapidly change ambient temperature (for example, air conditioning) and actions that mitigate longer-term thermal challenges of climate change (for example, low-carbon energy and active transport).

subjective feelings of thermal comfort, and investigate whether and how these go beyond the thermosensory afferent input to the brain.

Humans deploy a range of actions to achieve a form of extended thermal homeostasis. For example, we may – when hot – seek shade, drink water, remove clothing, switch on air conditioning or plant trees around our houses. These actions differ in timescale, effort, effect on thermal comfort, and consequential effects elsewhere. Every thermal stimulus or change in climate therefore represents a challenge for human decision-making systems, which must try to optimize the relation between action costs and thermal comfort benefits. Here we highlight two forms of behavioural adaptation that may be particularly important under conditions of climate change: mobility and thermal agency.

Mobility. Humans, similar to other animals, frequently move away from thermal stressors towards zones of thermal comfort. This thermomobility operates over timescales that range from individual sensorimotor actions to seasonal or permanent migration. Research on neural mechanisms of navigation has only recently begun to integrate temperature as an important driver of mobility[9]; however, it is likely that thermomobility is driven by at least three distinct cognitive strategies. The first is gradient-following behaviour (such as moving away from a draughty window), which might reflect a relatively direct link between thermal sensation and motor output. Second, prior knowledge can guide thermal mobility (in hot weather, we head to places that we know are cool) and can overcome local obstacles to gradient-following strategies. For example, if the mountains are known to be cool, it may be worth crossing hot plains to get to them. This suggests the involvement of model-based decision-making. Third, humans may practice 'thermal foraging', and explore in search of thermal comfort even when this conflicts with thermal gradient following. Understanding how such general-purpose behavioural control strategies may guide human thermal decisions will be important for understanding human adaptation to climate change.

Thermal agency. The cognitive flexibility, wide behavioural repertoire and sense of agency that characterize human behaviour has allowed us to control our thermal environment through external technologies, such as fire, clothing, housing and air conditioning. A sense of agency requires sensory outcome events to be attributed either to one's actions or to some other cause. For example, we may associate our switching on the air conditioning with feeling more comfortable. Because we tend to link actions to outcome events that are nearby in space and time[10], more remote consequences of action (such as excess heat produced elsewhere, or contributing to global warming through the carbon emissions generated by air-conditioning systems) may not form part of our sense of agency. However, learning the true effects of one's actions remains possible. Information and education can help us to understand how our own thermal agency affects anthropogenic climate change. A neuroscientific understanding of the mechanisms that underlie agency learning[10] could provide insights into ways to reduce, mitigate and prevent the harmful effects of climate change.

Individuals may feel that their personal thermal agency is but a drop in the ocean when it comes to climate change. In part, this may be because humans are a social species. We have evolved a level of organization in which individual agency is often delegated to leaders, who are given power and responsibility to manage complex outcome horizons, and balance interests across members of society. Leaders therefore have a distinctive responsibility to understand the effects of human activity across space and time, to be informed about anthropogenic thermal agency, and to attempt to secure thermal environments for the benefits of all. To achieve this, leaders can (and sometimes do) use decision-making principles that are broader and more sophisticated than those guiding a single individual's thermal behaviours. Leadership strategies can therefore promote climate resilience at a societal level.

Conclusions

Neural systems clearly support rheostatic adaptation to sustained heat, yet the circuit, cellular and plasticity mechanisms that set the range and limits of this adaptation remain poorly defined. Identifying how thermoregulatory circuits reorganize, where compensation fails, and how these processes interact with higher-order behavioural and cognitive control will be essential for understanding true neural heat tolerance. Resolving these gaps will not only refine fundamental principles of neural adaptation but also illuminate how thermal agency might be harnessed – or constrained – in a warming world.

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References

1. Romanovsky, A. A. The thermoregulation system and how it works. *Handb. Clin. Neurol.* **156**, 3–43 (2018).
2. Marder, E., Haddad, S. A., Goeritz, M. L., Rosenbaum, P. & Kispersky, T. How can motor systems retain performance over a wide temperature range? Lessons from the crustacean stomatogastric nervous system. *J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol.* **201**, 851–856 (2015).
3. Taylor, N. A. S. Human heat adaptation. *Compr. Physiol.* **4**, 325–365 (2014).
4. Gordon, C. J. *Temperature Regulation in Laboratory Rodents* (Cambridge Univ. Press, 1993).
5. Horowitz, M. Heat acclimation, epigenetics, and cytoprotection memory. *Compr. Physiol.* **4**, 199–230 (2014).
6. Ambroziak, W. et al. Thermally induced neuronal plasticity in the hypothalamus mediates heat tolerance. *Nat. Neurosci.* **28**, 346–360 (2025).
7. Chen, B. et al. Heat acclimation in mice requires preoptic BDNF neurons and postsynaptic potentiation. *Cell Res.* **35**, 224–227 (2025).
8. Horowitz, M. & Hasin, Y. Vascular compliance and left ventricular compliance cross talk: implications for using long-term heat acclimation in cardiac care. *Front. Physiol.* **14**, 1074391 (2023).
9. Vöröslakos, M. et al. ThermoMaze behavioral paradigm for assessing immobility-related brain events in rodents. *eLife* **12**, RP90347 (2025).
10. Zhao, K., Dang, J., Gu, J., Fu, X. & Haggard, P. Cognitive mechanisms underlying sense of agency: meta-analytic reviews of behavioral and neuroimaging studies. *Psychol. Bull.* **151**, 1307–1335 (2025).

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Competing interests

The authors declare no competing interests.