Symposium

Janus in Thermosensation: The Dual Interoceptive–Exteroceptive Nature of Thermal Signals in Body Ownership

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Thermosensation has traditionally been studied for its essential role in survival, enabling detection of environmental thermal stimuli and the maintenance of thermal homeostasis. Interestingly, unlike most sensory systems, thermosensation provides information about both the external world and the body's internal physiological state. In this review, we conceptualize these two dimensions as exteroceptive thermosensation, which conveys information about the thermal properties of external objects and the environment, and interoceptive thermosensation, which conveys information about the body's thermal state. Growing evidence suggests that this dual nature serves functions that extend beyond survival and homeostasis. Alterations in both thermal perception and thermoregulation have been associated with changes in body ownership, the experience that one's body belongs to oneself, while manipulations of thermal signals can influence ownership itself. Here, we review the physiological and neural bases of exteroceptive and interoceptive thermosensation, from peripheral encoding to central processing, and examine their relationship with body ownership in healthy and clinical populations. We discuss evidence suggesting partially distinct yet potentially convergent neural substrates for these two dimensions of thermosensation, highlighting the insular cortex and its broader connectivity network as a candidate through which thermal information may sustain body ownership. Finally, we consider how emerging neurotechnologies offer new opportunities to investigate the contribution of thermosensation to body ownership while also opening novel avenues for neurorehabilitation. We propose that thermosensation represents an underexplored contributor to body ownership, opening new avenues for future research on how bodily and environmental thermal signals are integrated to support the sense of self.

Key words: bodily self-awareness; insula; ownership; temperature; thermosensation

Significance Statement

Thermosensation is traditionally linked to homeostasis and survival. However, a growing body of evidence suggests that thermal signals also contribute to body ownership, the experience that one's body belongs to oneself. Here, we integrate findings from neuroscience, clinical neurology, and neuroengineering within an exteroceptive–interoceptive framework of thermosensation. We discuss how thermal signals from both the environment and the body may contribute to maintaining a coherent sense of the self, identify potential candidate neural systems that support this interaction, and highlight thermosensory neuroprosthetics as a promising approach to investigating the role of thermal signals in body ownership.

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Introduction

Thermosensory signaling is essential for survival. Across species, thermal signals support adaptive behavior, tissue protection, energy regulation, and physiological stability by continuously informing the nervous system about both environmental conditions and bodily thermal state (Cannon, 1929; Romanovsky,

2007, 2014, 2018; Tansey and Johnson, 2015). Unlike many sensory systems that primarily encode either external stimuli or internal physiological states, the thermosensory system encompasses both exteroceptive [objects and environmental thermal information (Jänig, 2018)] and interoceptive [skin and internal body thermal information (Romanovsky, 2018)] dimensions (Crucianelli et al., 2025). This dual organization suggests that thermosensation can be conceptualized within an exteroceptive–interoceptive framework, as thermal signals provide information about both the external environment and the body's physiological condition. Consequently, thermosensation occupies a unique position at the interface between environmental and self-bodily sensing. Importantly, from a physiological perspective, although the relationship between exteroceptive and interoceptive thermosensation remains debated, thermal perception and body temperature regulation are closely intertwined (Romanovsky, 2014). Nevertheless, these two processes seem to involve distinct neural networks (Craig et al., 2000; Hua et al., 2005; Morrison et al., 2008; Morrison, 2011; Peltz et al., 2011; Fardo et al., 2017; Madden and Morrison, 2019; Carta et al., 2026).

Understanding the functional implications of the dual nature of thermosensation has become an important focus of recent research. Indeed, beyond the crucial role of thermosensory systems for human survival and interaction within the environment, a growing body of research demonstrates that these two types of information contribute to bodily self-awareness (Salvato, 2025; Salvato and Crucianelli, 2025). Bodily self-awareness is a multidimensional construct involving the experience of owning a body (body ownership); the experience of being a body with a given location within our environment (self-location); the experience of taking a first-person, body-centered perspective on that environment (perspective); and the experience of being the actor of our actions (sense of agency; Tsakiris et al., 2010; Blanke, 2012; Blanke et al., 2015; Grivaz et al., 2017; Salvato et al., 2020). Among others, body ownership seems particularly linked to interoceptive and exteroceptive thermosensation. Indeed, pathological or temporary alterations in body ownership are associated with reduced skin temperature and altered detection of innocuous thermal stimuli (see, for a recent review, Salvato and Crucianelli, 2025). However, due to the intrinsic, largely unknown nature of thermosensation in humans, its neurophysiological link to body ownership remains unclear. Recent advances in other disciplines, through bottom–up, peripheral approaches such as haptics or neural interfaces, are providing novel opportunities to experimentally investigate these questions from a different perspective. Emerging neuroprosthetic approaches increasingly attempt to restore naturalistic external thermosensation in amputees, i.e., exteroceptive, by reconstructing thermosensory signaling from the periphery (Iberite et al., 2023; Shokur et al., 2026). Such approaches not only improve sensory restoration but may also provide a model for investigating how thermosensation contributes to body ownership (over the prosthesis).

Here, we propose that the defining feature of thermosensation for body ownership lies in its dual capacity to simultaneously signal the body's thermal state and environmental thermal information. Firstly, we review evidence for the neurophysiological mechanisms underlying interoceptive and exteroceptive thermosensation, and then we highlight how these dimensions may also contribute to the sense of body ownership. We further explore whether physiologically distinct thermosensory processes converge onto partially overlapping neural substrates that are also involved in body ownership. Finally, we discuss open questions, future directions, and the potential of thermosensory neuroprosthetic restoration as a tool to investigate the role of thermal signals in constructing the bodily self.

The Dual Nature of Thermosensation

Exteroceptive thermosensation: sensing the external world

We refer to exteroceptive thermosensation as the conscious perception of thermal stimuli arising from the skin. Exteroception provides continuous information about the temperature of external objects and environmental conditions, supporting adaptive interactions with the environment. Current understanding of the neural mechanisms underlying exteroceptive thermosensation derives largely from animal research. Thermal stimuli are detected by specialized cutaneous thermoreceptors, where thermal transduction is mediated by temperature-sensitive ion channels belonging to the transient receptor potential (TRP) family, among others (Xiao and Xu, 2021). Key channels include TRPM8, which is critically involved in peripheral encoding and perception of both cool and warm sensation, TRPA1 in noxious cold, and TRPM2/TRPV3/TRPV4 channels, which contribute to innocuous warmth perception (McKemy et al., 2002; Patapoutian et al., 2003; Dhaka et al., 2006).

Thermal information is conveyed from the skin to the central nervous system primarily by myelinated Aδ fibers and unmyelinated C fibers innervating the skin, which differ in diameter, conduction velocity, and response properties (Darian-Smith et al., 1973). Thermoreceptors exhibit a spontaneous baseline firing rate that varies with skin temperature, enabling continuous signaling of thermal information (Darian-Smith et al., 1973, 1979; Darian-Smith and Johnson, 1977; Darian-Smith, 1981). Recent studies examining thermoreceptor population encoding of innocuous temperatures show that the most common functional response type is thermoreceptors that increase activity in response to cooling and decrease activity in response to warming (Paricio-Montesinos et al., 2020; Bokiniec et al., 2026).

Thermoreceptors project predominantly to laminae I and II of the dorsal horn, where thermal information enters ascending somatosensory pathways (Craig, 2002). In rodents, these signals ascend via spinothalamic pathways to multiple thalamic targets that, in turn, project to the primary somatosensory cortex and the posterior insular cortex, which underpin thermal perception (Paricio-Montesinos et al., 2020; Leva and Whitmire, 2023; Vestergaard et al., 2023; Carta et al., 2026). Some properties of thermal responses appear hard-wired from the periphery to the thalamus and cortex, for example, cooling evokes both transient and sustained responses with short latency, whereas warming produces longer latency and predominantly sustained activity patterns. However, others show progressive transformation, for example, cooling-excited neurons and warming-suppressive responses appear more highly represented in subcortical than cortical stages (Bokiniec et al., 2026), and increasingly diverse thermal tuning profiles emerge at the level of the posterior insular cortex (Vestergaard et al., 2023). Notably, although S1 contains cool-responsive neurons, the posterior insula contains both warm- and cool-tuned neurons, suggesting that it serves as the primary cortical representation of temperature (Vestergaard et al., 2023). Evidence in humans remains comparatively limited but supports a broadly similar cortical organization (Leva and Whitmire, 2023). Neuroimaging and lesion studies have implicated the posterior insula as a key cortical region for thermal perception (Davis et al., 1999; Craig et al., 2000; Hua et al., 2005;

Fardo et al., 2017). Beyond the insula, thermal stimulation activates a broader cortical network including primary and secondary somatosensory cortices, anterior cingulate cortex, orbitofrontal cortex, and parietal regions, suggesting that exteroceptive thermosensation engages distributed neural systems extending beyond sensory discrimination alone (Hua et al., 2005; Rolls et al., 2008; Peltz et al., 2011).

Interoceptive thermosensations: skin and internal bodily thermal state

Alongside the perception of external thermal stimuli, thermosensory signaling contributes to interoception by providing continuous information about the body's internal thermal state and its homeostatic regulation. Such signals may arise from both the skin, which provides information about the shell's thermal state, and visceral afferents related to internal thermal conditions. These mechanisms enable sensing and initiation of physiological or behavioral responses to maintain thermal balance (Morrison, 2011; Romanovsky, 2018; Crucianelli and Ehrsson, 2023; Crucianelli et al., 2025).

As with exteroception, current understanding of the neural mechanisms underlying interoceptive thermosensation also derives largely from animal research. Thermoregulatory processing relies on a distributed network extending from peripheral thermoreceptors to spinal, brainstem, hypothalamic, and forebrain structures. In addition to cutaneous inputs, evidence suggests that thermally responsive visceral afferents contribute to thermoregulatory signaling. These pathways, which include vagal afferents projecting to the nucleus tractus solitarii, provide a route through which information related to the body's thermal state can access central homeostatic networks (Romanovsky et al., 1997; Székely et al., 1997; Nagashima et al., 2000; Székely, 2000; Critchley and Harrison, 2013; Morris et al., 2017; Chang, 2019; Gers-Barlag et al., 2025). It should be noted that these same visceral afferents also convey chemical (e.g., inflammatory, metabolic) and mechanical signals, which contribute substantially to interoceptive processing and likely participate, alongside thermal signaling, in the bodily self-awareness processes discussed in this review (Critchley and Harrison, 2013; Berntson and Khalsa, 2021).

Thermal signals arising from the skin are relayed through lamina I neurons of the spinal cord toward the lateral parabrachial nucleus (LPB), a key relay for thermoregulatory information (Morrison et al., 2008; Nakamura and Morrison, 2008). While there is ongoing debate about the degree of overlap among projection neurons that innervate the parabrachial nucleus or thalamus, at least some spinal projection neuron populations can form parallel ascending pathways (Hylden et al., 1989; Choi et al., 2020; Alsulaiman et al., 2021). Distinct neuronal populations within the LPB respond preferentially to cooling and warming stimuli and project to hypothalamic regions such as the preoptic area (POA), which are involved in homeostatic regulation (Nakamura and Morrison, 2008). Moreover, animal studies have identified specialized thermosensitive neuronal populations within the POA that integrate peripheral and central thermal information and coordinate autonomic, endocrine, and behavioral responses necessary for maintaining thermal homeostasis (Tan and Knight, 2018). Through their downstream projections, these circuits regulate multiple thermoregulatory effectors, including cutaneous vasomotor responses, brown adipose tissue thermogenesis, shivering, and heat-dissipation behaviors (Morrison et al., 2008; Nakamura and Morrison, 2008).

Where interoceptive thermal information is processed in the cortex remains unclear, as the neural architecture supporting thermoregulation in humans remains poorly characterized. Current evidence suggests a multilevel, hierarchically organized system involving cortical and subcortical nodes (Muzik and Diwadkar, 2016; Muzik et al., 2020, 2022). The midbrain, pons, and POA constitute a homeostatic subnetwork (autonomic) at the lowest level. The insula forms the interoceptive subnetwork, and the prefrontal cortex, orbitofrontal cortex, and anterior cingulate cortex comprise the executive subnetwork, which also receives modulatory input from primary sensory cortical regions in the parietal lobe. The homeostatic subnetwork would help create maps of the body's current physiological state, sending information to the interoceptive subnetwork to generate emotional responses related to interoceptive processes. The executive subnetwork would modulate behavioral thermoregulation (Muzik et al., 2020).

Thermosensation and Body Ownership

Growing evidence in humans suggests that exteroceptive and interoceptive thermosensation, although carrying different information, contribute to the construction of the sense of body ownership (Blanke, 2012; Guterstam et al., 2019; Ehrsson, 2020; Salvato et al., 2020). Among the sensory signals contributing to body ownership (e.g., visual, tactile, vestibular), thermosensory cues may be particularly relevant because they simultaneously convey information about interactions with the external environment and provide continuous cues about the body's physiological state (for a recent review, see Salvato and Crucianelli, 2025).

Studies in healthy individuals indicate a close relationship between thermosensation and body ownership. Experimental manipulations that alter ownership are frequently accompanied by changes in both interoceptive and exteroceptive thermosensation. For example, the induction of the rubber hand illusion has been associated with a decrease in the participant's real hand skin temperature, suggesting that altered ownership may influence the thermal regulation of the body surface (Moseley et al., 2008; Tsakiris et al., 2011). Although findings from rubber hand illusion studies have not always been consistent (de Haan et al., 2017), variability may partly reflect differences in task characteristics and the specific mechanisms through which ownership is manipulated. Importantly, converging evidence has emerged from other embodiment paradigms. Reduced limb temperature has been observed during both the full body illusion and the mirror box illusion (Salomon et al., 2013; Crivelli et al., 2021, 2023; Salvato et al., 2025a). Both paradigms were also associated with reduced sensitivity to thermal stimuli (Llobera et al., 2013; Crivelli et al., 2021), suggesting that ownership manipulations can simultaneously affect interoceptive and exteroceptive thermosensation.

Importantly, evidence from neurological populations points in the same direction. Patients with disturbed body ownership exhibit both altered skin temperature regulation and impaired perception of warm and cold stimuli (Salvato et al., 2018, 2022, 2025a,b; Moro et al., 2024). On the other hand, thermosensory signals can also influence ownership. Experimental manipulations of peripheral temperature modulate embodiment, with warming reducing susceptibility to the rubber hand illusion and cooling enhancing it (Kammers et al., 2011). In addition, visuothermal congruency has been shown to strengthen embodiment, whereas mismatches between seen and felt thermal stimulation reduce ownership experiences (Trojan et al., 2018; Crucianelli and Ehrsson, 2022).

At first glance, these findings may appear to reflect a circular relationship: manipulations of body ownership alter both skin temperature and thermal perception, whereas manipulations of thermosensations can, in turn, influence ownership. We suggest that this apparent circularity may instead reveal the fundamental dual property of thermosensation that is linked to ownership. By simultaneously signaling the body's internal thermal state and external thermal information, thermosensation operates at the interface between body and world. From this perspective, body ownership may depend, at least in part, on the integration of interoceptive and exteroceptive thermosensory information (Salvato, 2025). If so, a key question becomes where and how interoceptive and exteroceptive thermosensation converge within the nervous system to support body ownership.

Where Do Exteroceptive and Interoceptive Thermosensations Integrate to Support Body Ownership?

The available evidence suggests that thermosensation contributes to body ownership not simply through its interoceptive or exteroceptive dimensions in isolation but through their integration. This raises a fundamental question: where and how are these distinct thermosensory dimensions integrated within the brain?

One potential candidate is the insular cortex. Across both animal and human studies, the insula has been consistently implicated in thermosensory processing, interoception, and body ownership. Classical models (Craig, 2003, 2009, 2010, 2011) describe the insula as a hierarchical processing system in which bodily signals are progressively re-represented along a posterior-to-anterior axis, moving from posterior primary representations of external sensory input and physiological states toward increasingly integrated and consciously accessible experiences. Recent evidence in humans supports this possibility (Salvato et al., 2025b). In patients with a disturbed sense of ownership following right-hemisphere stroke, both alterations in skin temperature regulation and deficits in thermal perception have been associated with lesions involving the insular cortex. Importantly, however, these impairments were linked to partially distinct insular regions. Abnormalities in skin temperature regulation, which we interpret within the present framework as potentially reflecting disturbances in interoceptive thermosensation, were associated with relatively more posterior lesions. In contrast, deficits in perceiving warm and cold stimuli, which we interpret within the present framework as potentially reflecting disturbances in exteroceptive thermosensation, were associated with lesions extending into more anterior insular sectors compared with interoceptive thermosensation deficits (Salvato et al., 2025b). Notably, the objective alteration in skin temperature regulation—indexing a disturbance in interoceptive thermosensation—did not translate into a conscious percept in patients, who were unable to spontaneously report it. In contrast, the deficit in exteroceptive thermosensation, i.e., in perceiving warm and cold stimuli, was explicitly reported by patients when directly questioned. This anatomo-functional dissociation—between a physiological alteration that remained inaccessible to consciousness and a perceptual deficit that was explicitly accessible—is consistent with models proposing a posterior-to-anterior gradient in insular processing (Craig, 2010). Within this framework, relatively posterior insular regions may support primary representations of thermal bodily states, whereas more anterior sectors may contribute to integrating bodily signals into consciously accessible thermal percepts. Such an organization may provide a potential substrate through which interoceptive and exteroceptive thermosensations are progressively integrated to support body ownership.

However, body ownership is unlikely to emerge solely from insula activity. Converging evidence indicates that it depends on the coordinated activity of a distributed network including premotor, sensorimotor, temporoparietal, and insular regions (Grivaz et al., 2017; Salvato et al., 2020; Moro et al., 2022). From this perspective, understanding how exteroceptive and interoceptive thermosensation contribute to body ownership requires moving beyond characterizing individual cortical loci and considering broader cerebral networks in which these processes may converge. To provide an illustrative characterization of the large-scale networks that may support the contributions of exteroceptive and interoceptive thermosensation to body ownership, we used the publicly available Neurosynth platform (http://neurosynth.org/), a large-scale framework for automated synthesis of functional magnetic resonance imaging data derived from thousands of published neuroimaging studies (Yarkoni et al., 2011). Seed locations were derived from a previous lesion-mapping study that identified dissociable neural substrates underlying deficits in exteroceptive thermosensation (i.e., impaired perception of thermal stimuli) and interoceptive thermosensation (i.e., altered lower-limb temperature regulation) in patients with disorders of body ownership (Salvato et al., 2025b). The peak coordinates associated with exteroceptive thermosensation ($x = 35$; $y = -1$; $z = 17$) and interoceptive thermosensation ($x = 46$; $y = -11$; $z = 16$), reported in Montreal Neurological Institute space, were entered separately as seeds into Neurosynth, which estimates whole-brain resting-state connectivity patterns based on a large normative dataset of healthy individuals (Yarkoni et al., 2011). The resulting maps are presented for illustrative and hypothesis-generating purposes and should not be interpreted as novel empirical findings. The resulting connectivity maps were downloaded and visualized using a threshold of Fisher's $z > 0.2$. Visual inspection revealed both distinct and overlapping connectivity patterns associated with the two seed regions. Notably, the overlap between the exteroceptive and interoceptive thermosensation-related networks encompassed regions classically implicated in bodily ownership (Tsakiris et al., 2007; Tsakiris, 2010; Grivaz et al., 2017; Park and Blanke, 2019; Salvato et al., 2020; Moro et al., 2022), including the supplementary motor area, precentral gyrus, postcentral gyrus, Rolandic operculum, superior temporal gyrus, and supramarginal gyrus (Fig. 1). These convergent connectivity patterns are consistent with the possibility that a distributed functional connectivity network supports the contribution of exteroceptive and interoceptive thermosensation to body ownership. Future ad hoc neuroimaging studies may shed new light on this topic.

Neuroengineering of Thermosensation: From Sensory Restoration to Body Ownership

The framework proposed here generates a testable prediction: if thermosensation contributes to body ownership by integrating thermal information about the body and the environment, then restoring thermosensation after sensory loss should influence not only thermosensory mechanisms but also aspects of body ownership. Recent advances in neuroengineering offer an opportunity to directly evaluate this prediction. By reconstructing thermosensory input at the peripheral level, these approaches provide a complementary perspective to lesion studies, allowing

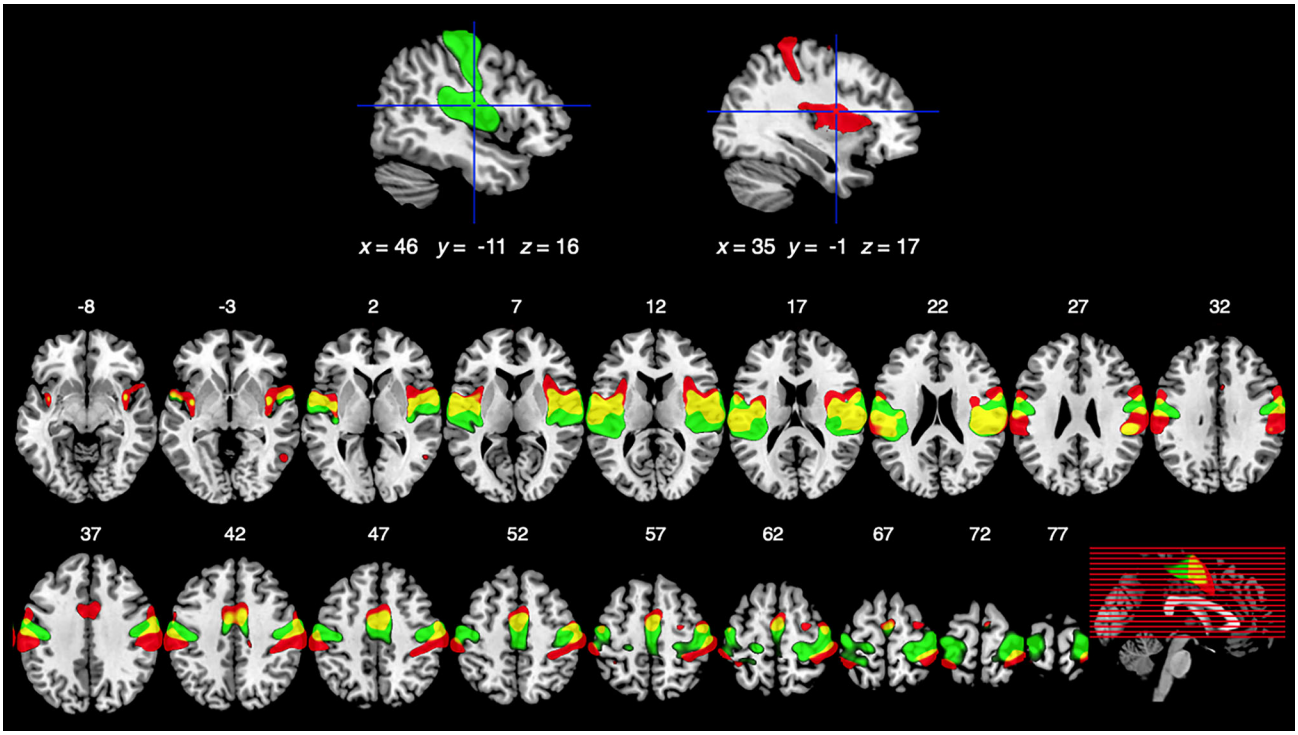


Figure 1. Hypothesis-generating visualization of large-scale functional networks associated with exteroceptive and interoceptive thermosensation. Seed-based functional connectivity maps were generated using Neurosynth from lesion-derived peak coordinates previously associated with deficits in exteroceptive thermosensation, in red ($x = 35$; $y = -1$; $z = 17$), and interoceptive thermosensation, in green ($x = 46$; $y = -11$; $z = 16$), in patients with disturbances of body ownership (Salvato et al., 2025b). Connectivity patterns were estimated using resting-state data from healthy individuals and thresholded at Fisher's $z > 0.2$. The overlap between the two connectivity maps (yellow) encompassed regions classically implicated in body ownership, including the supplementary motor area, precentral gyrus, postcentral gyrus, Rolandic operculum, superior temporal gyrus, and supramarginal gyrus.

researchers to investigate how exteroceptive and interoceptive thermal signals contribute to embodiment over the prosthesis from the bottom up.

Within this background, neural interfaces provide novel opportunities for investigation. Emerging approaches, particularly in prosthetic users (Shokur and Micera, 2024), aim to restore naturalistic thermal sensations in individuals with sensory loss or limb amputation by reconstructing peripheral thermosensation. A major challenge in neural interfaces for sensory restoration is to reproduce percepts that are both homologous, corresponding to the appropriate sensory modality, and somatotopically accurate, arising from the appropriate location of the missing limb (Shokur et al., 2026). One approach that has met both requirements, demonstrated in recent studies in upper-limb amputees, relies on phantom thermal maps: thermal stimulation of specific regions of the residual limb evokes localized thermal sensations in the phantom hand (Iberite et al., 2023; Muheim et al., 2024). These approaches rely on noninvasive stimulation of skin regions reinnervated by transacted peripheral nerves following amputation (Ortiz-Catalan, 2024). Surgical procedures such as targeted sensory reinnervation (reconnecting the severed cutaneous nerve to sensory end organs in areas of uninjured skin in the residual limb) may further increase the precision and extent of these thermal maps.

In principle, implantable neural interfaces targeting peripheral nerves, the spinal cord, or the brain could also restore thermosensation. In practice, however, reliably engaging thermosensory pathways remains difficult, largely because thermal afferents have substantially smaller diameters than motor or tactile sensory fibers. Achieving functional selectivity requires activating one fiber type while sparing others. This is a major technical challenge because, during extracellular electrical stimulation, activation thresholds are inversely related to axon diameter, with larger fibers recruited before smaller ones (Mortimer and Bhadra, 2009), meaning that stimulation amplitudes strong enough to recruit small-diameter fibers will also activate larger, lower-threshold fibers nearby. Several strategies have been proposed to achieve diameter-specific selectivity despite this constraint. These include shaping stimulation waveforms to preferentially engage particular fiber populations, applying high-frequency stimulation to selectively block conduction in target fibers (Patel and Butera, 2018), and current-steering approaches that spatially bias activation toward specific fiber types (Rossetti et al., 2025). Among other possible approaches, focused ultrasound (Lemaire et al., 2021) might enable the preferential recruitment of thermosensitive afferents [as shown computationally (Lemaire et al., 2021)]. Reports of thermal percepts elicited by intracortical stimulation (Penfield and Faulk, 1955; Mazzola et al., 2012; Flesher et al., 2016) suggest that central neurostimulation may also be feasible, although this possibility has yet to be systematically investigated.

Importantly, these approaches aimed at restoring thermosensation may also provide alternative experimental models for investigating how interoceptive and exteroceptive thermosensation may differentially contribute to body ownership by targeting distinct afferents. Beyond its value as an experimental model, restoring thermal sensation has strong translational value by providing direct benefits that boost prosthetics use. Improved thermal feedback may support more natural interactions with the environment by enabling users to perceive objects' thermal properties and detect potentially harmful temperatures. More interestingly, given that thermosensory signals contribute to the

construction and maintenance of body ownership, restoring these signals may help reconstruct aspects of bodily self-awareness that are often disrupted following limb loss or severe sensory impairment. From this perspective, thermal neuroprosthetics may improve not only sensory function but also the experience of embodiment of the artificial limb, thereby supporting its acceptance and spontaneous use in daily life.

Conclusions and Future directions

Thermosensation occupies a position of duality within the nervous system because it simultaneously conveys thermal information about the external environment and the body's internal physiological state. Traditionally, exteroceptive and interoceptive thermosensation have been studied primarily in relation to homeostasis and survival. Here, we reviewed converging evidence suggesting that both dimensions may also contribute to body ownership. Studies in healthy and pathological populations indicate that alterations in body ownership are associated with changes in both thermal perception and skin temperature and that manipulations of thermal signals can, in turn, influence ownership. These observations raise the possibility that body ownership depends, at least in part, on both interoceptive and exteroceptive thermosensation.

Several major questions remain unresolved. A central challenge concerns the psychophysical relationship between interoceptive and exteroceptive thermosensation themselves. Although available evidence suggests partially distinct physiological and neural substrates, the extent to which these systems interact and converge remains poorly understood. Future work combining measures of peripheral thermoregulation, core body temperature, thermal perception, and ownership experience in healthy and clinical populations will be essential for determining how information about the body's physiological state and its thermal interactions with the environment is integrated at the perceptual level.

A second challenge concerns identifying the neurophysiological mechanisms through which thermosensation contributes to body ownership. The evidence reviewed here suggests that the insular cortex may serve as an important hub within a broader distributed network that also involves regions associated with body ownership processes. However, the precise cellular and circuit mechanisms by which interoceptive and exteroceptive thermosensory signals converge and interact with body ownership networks remain largely unknown. Future work using functional neuroimaging in humans and cellular resolution neural circuit analysis in mice will help clarify these mechanisms.

Importantly, investigating body ownership in clinical populations with altered thermosensation may provide further insights. For example, although altered thermosensory processing, including heat sensitivity and impaired thermal perception, is well documented in multiple sclerosis (Christogianni et al., 2018, 2022), the extent to which patients experience changes in the perceived temperature of affected body parts (Konik et al., 2024) and whether such alterations relate to disturbances in body ownership (Risso et al., 2025) remain largely unexplored.

Moreover, recent advances in thermosensory neuroengineering offer an opportunity to move beyond top–down evidence and directly test the hypotheses outlined in this review. By restoring thermosensations, neuroprosthetic approaches may reveal whether reconstructing thermal information influences embodiment over the prosthesis, helping to establish whether the integration of interoceptive and exteroceptive thermosensory signals constitutes a fundamental component of body ownership.

Finally, the therapeutic potential of thermosensation may also extend beyond neuroprosthetics. In the field of neurorehabilitation, peripheral thermal stimulation could represent a promising avenue for patients with disturbances of body ownership following neurological damage. If thermosensory signals help maintain coherent representations of the body, interventions targeting thermosensory pathways may reinforce representations of affected body parts and promote their reintegration into the bodily self. Although this possibility remains largely unexplored, future studies should investigate whether controlled thermal stimulation can enhance ownership-related rehabilitation outcomes (Shokur et al., 2026), either as a stand-alone intervention or in combination with established multisensory approaches (Risso and Bassolino, 2022).

Together, these developments may help determine whether the integration of interoceptive and exteroceptive thermosensory signals represents a fundamental mechanism through which the nervous system constructs and maintains the experience of the body as one's own.

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