



Embodying the default mode network: self-related processing from an embodied perspective

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Self-related processes in the default mode network (DMN) have been viewed predominantly through a cognitive lens, often overlooking the embodied dimensions of self. This paper proposes an embodied reconceptualization of DMN function by revisiting its two key self-related processes: self-relevance and self-reference. We argue that self-relevance is rooted in interoceptive inference and value estimation, assessing stimuli based on their predicted long-term impacts on internal bodily states. We introduce the notion of ‘affective maps’ — internal models of internal bodily state that parallel cognitive maps, which are internal models of the external world. We further reinterpret self-reference through the lens of second-order cybernetics, framing the DMN as a core component of a reflexive, nontrivial brain–body system, which monitors and regulates the internal milieu through bidirectional brain–body loops. This systems-level view integrates insights from interoception, affective neuroscience, and cybernetics, positioning the DMN as an embodied internal model crucial for constructing and regulating selfhood.

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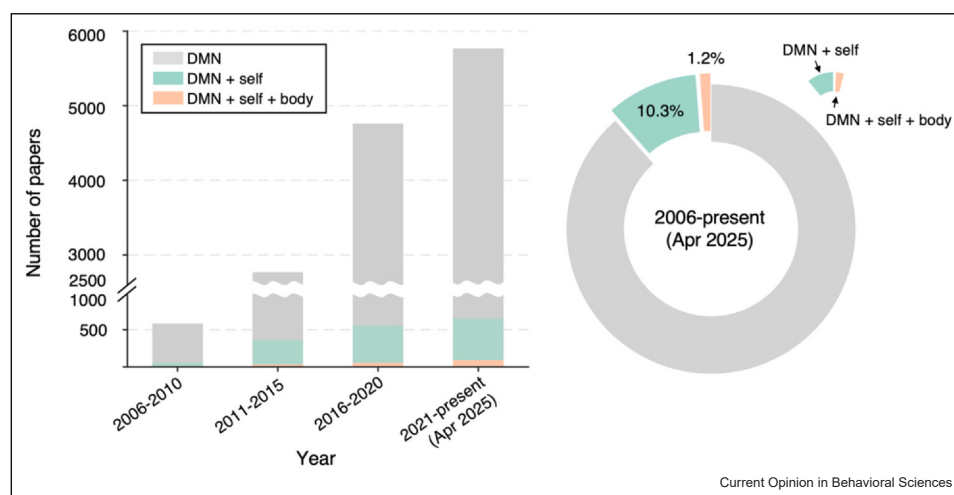
Introduction

The default mode network (DMN) comprises a group of brain regions, including ventromedial and dorsomedial prefrontal cortices, posterior cingulate cortex (PCC), medial temporal lobe, and superior temporal cortices [1]. Studies have shown that regions of the DMN are involved in self-related processes, such as autobiographical memory [2], reflection on one’s personality traits [3], and the processing of self-relevant information [4–6]. In studies of the DMN functions in self-related processing, most research has focused on the conceptual and psychological aspects of the self. However, it is important to acknowledge that the self also encompasses significant bodily dimensions, such as the physical self — one of the two primary dimensions of the self, alongside the psychological self [7].

Revisiting the bodily dimensions of the self

Throughout the long history of the studies of the self, the importance of the body has been emphasized across multiple fields. In biology, Jakob von Uexküll introduced the concept of *Umwelt*, meaning environment in German, to denote the unique surroundings each organism experiences through the sensory and motor systems embedded in its body plan [8]. Although the term *Umwelt* was later adapted to describe the subjective representation of the world [9], Uexküll originally placed the body at the center of each organism’s construction of its unique perceptual world. In psychology, William James also described the body as an essential part of the self, referring to it as the ‘material self’ [10]. Subsequently, several theorists consistently emphasized the importance of the body in their theories of the self. For instance, Ulric Neisser emphasized the body as the primary locus of perception and action, referring to it as the ‘ecological self’ — the perceived self directly from the ‘continuous flow of optical information’ [11]. Also, Shaun Gallagher described the ‘minimal self’ [12] as the most basic sense of being a self, including body ownership (e.g. feeling that one’s body is one’s own) and body agency (e.g. one is in control of one’s body). Antonio Damasio emphasized the body as a foundation of consciousness through his conception of the ‘proto-self,’ referring to the continuous mapping of bodily signals [13]. Despite varied terminology, there is a general agreement that the body plays a crucial role in forming selfhood, the subjective experience of being a self [14].

Figure 1



Limited emphasis on the bodily dimension in DMN and self-related research. To assess the extent to which research on the DMN incorporates the bodily dimension of self, we conducted a literature search on PubMed (2006-April 2025) using selected keywords. The left panel shows the number and proportion of papers containing specific keywords “DMN” or “default mode network” (gray + green + orange), “self” (green + orange), and body-related terms (orange) over time. Body-related search terms include embody, embodiment, embodied, bodily, body, interoception, and interoceptive. The right panel summarizes these proportions across the entire period. Of 13,958 DMN-related papers, approximately 11.5% (1,607) also included the term “self”, while only 1.23% (172) additionally included body-related terms.

Beyond theoretical work, empirical studies also highlight the body as a key component of the self, resonating with the concept of the ‘embodied self’ [15] or ‘bodily self-consciousness’ [16]. Several behavioral tasks have been developed to target the bodily self. For example, the Rubber Hand Illusion demonstrates that congruent visual and tactile inputs can induce ownership over an artificial limb [17], while the Full Body Illusion shows that visual feedback of internal rhythms, such as respiration or heartbeat, can modulate perceived self-location [18]. These tasks have enabled the empirical investigation of the bodily dimensions of the self. In neuroscience, however, even though the DMN has been widely recognized as a core network for self-related processing, the contribution of the bodily self to DMN function has been relatively understudied. A PubMed search (see Figure 1 for details) indicates that the bodily dimension of self-related DMN activity remains under-represented in the literature.

In this paper, by focusing on two representative self-related functions in the DMN — self-relevance and self-referential processing [19] — we aim to reconceptualize these processes through the lens of embodiment. Self-relevance processing refers to the evaluation of the personal significance or proximity of a stimulus or event to the self, whereas self-referential processing involves metacognitive operations, such as introspection and self-assessment. Although these functions have predominantly been examined from the standpoint of the conceptual self, we undertake a theoretical re-

examination of the literature and propose new directions that integrate bodily processes into the understanding of these DMN-related functions.

Embodying self-relevance: an interoceptive and value-based account

Traditionally, studies in cognitive neuroscience have investigated self-relevance primarily through conceptual or social tasks, reporting DMN activation during self-relevance processing. These tasks include rating the personal relevance of emotional stimuli [20], comparing one’s name or face to others (e.g. romantic partners, friends, or strangers) [21,22], or associating cues with the self and others [23,24]. Most of these studies have found that processing or evaluating self-relevant information activates brain regions within the DMN, especially the cortical midline structures [19,21]. More recent work has extended these findings by showing that the DMN is crucial for predicting the perceived level of self-relevance during narrative processing and spontaneous thought [5,6].

However, many of these studies also reported the involvement of the salience network, including the anterior cingulate cortex (ACC) and anterior insula (aINS) [6,21,22], along with several subcortical regions such as the ventral striatum [5,6,20,22]. Similarly, in a recent large-scale connectome-based predictive modeling study, Zhang et al. [25] showed that individual differences in self-prioritization effects — the tendency to prioritize self-related stimuli over those related to others [26] — can be predicted from resting-state connectivity patterns

spanning the DMN, salience network, and subcortical regions, further supporting an integrative neural architecture of self-related processing. These suggest the contribution of interoceptive and reward-related processes to self-relevance evaluation [27–29], yet they have received limited attention. We aim to provide a fresh perspective on the collaborative contribution of the DMN, salience network, and subcortical regions to self-relevance processing by incorporating interoceptive inference and reinforcement learning (RL).

We propose that self-relevance processing is grounded in interoceptive predictions and their implications for the internal state of the body [29,30], which can also be conceptualized as the prediction of long-term rewards (i.e. value) [31] (see [Box 1](#) for definitions of key terms). Interoception is the process of monitoring and signaling internal physiological variables that constitute the internal bodily states — also referred to as the internal milieu or internal environment [32]. Such internal state variables constitute the viability zone that defines survival [33] — when they deviate significantly from the homeostatic range, survival is compromised, whereas maintaining these variables near the homeostatic set-point supports well-being [34]. In this sense, the distance from the homeostatic set-point within the internal state space can serve as a basis for a reward signal [35]. While rewards are often treated somewhat superficially in the field of RL — typically ignoring their relevance to internal states — there have been efforts to investigate them from a more fundamental and embodied perspective. For example, Singh et al. proposed that reward originates from the internal environment of an agent, emphasizing that “all rewards are internal” [36]. From this perspective, the value of a stimulus or event (i.e. expected future rewards) can also be re-conceptualized as its predicted capacity to impact the internal states [37], and estimating the interoceptive consequences for the internal states becomes functionally analogous to value estimation in the RL context.

Self-relevance can then be understood as an absolute (i.e. unsigned) value signal derived from simulated internal states. During the early stages of life, individuals learn to associate external stimuli with their direct interoceptive outcomes — for example, the positive consequences of a caregiver’s presence [38] or the negative consequences of loud noises [39]. Over development, these associations give rise to internal models that predict how various stimuli influence internal states in relation to homeostatic regulation, forming the foundation of affect [40]. Based on the internal models, if a stimulus or event is expected to impact internal homeostatic conditions — whether positively or negatively — it is likely to be perceived as self-relevant. Here, the internal model is the model of the internal bodily state, contrasted with the internal model of the external world

(i.e. world model), which has been extensively studied in the conventional model-based RL [41]. We hypothesize that the DMN plays an important role in representing the internal model of the internal environment, supporting self-relevance processing.

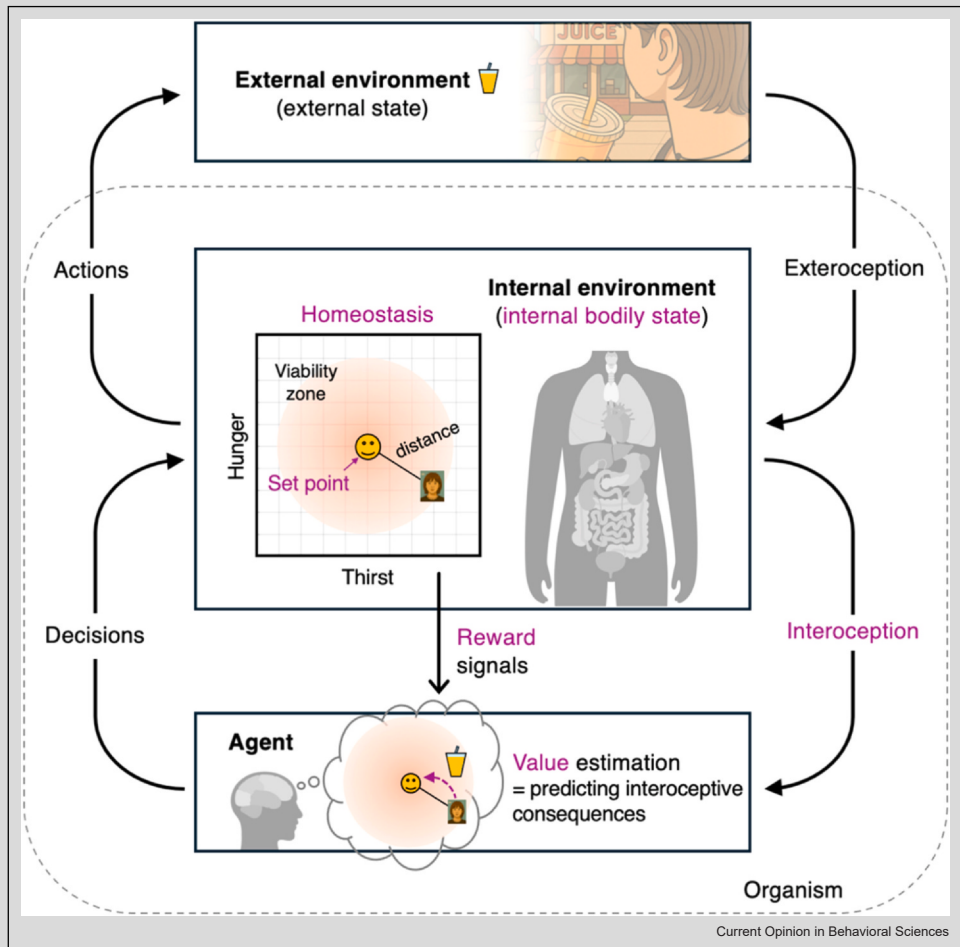
This view differs from the predominant approaches to self-relevance, which emphasize memory-based cognitive processes, such as the recognition of names, faces, or personal narratives. Instead, we propose that value-related processing lies at the core of the self-relevance processing, emphasizing its pragmatic and affective aspects. This perspective helps explain why value [42] and self-relevance processing converge in the DMN, particularly within the cortical midline structures such as the ventromedial prefrontal cortex (vmPFC), and why these processes often coactivate interoceptive and reward-related subcortical regions. This aligns with the Embodied Predictive Interoceptive Coding (EPIC) model, which posits that visceromotor regions, including the aINS, ACC, and medial prefrontal and orbitofrontal cortices, generate predictions about internal bodily states compared with ascending interoceptive signals, forming a basis for evaluating and predicting relevance in a given context [30]. In addition, classical brain regions involved in interoceptive and homeostatic processes — including brainstem nuclei (e.g. nucleus tractus solitarius and parabrachial nucleus) and hypothalamus [43,44] — are known to interact with the DMN, particularly the medial prefrontal cortex, playing a central role in autonomic and homeostatic regulation [45]. Furthermore, a large-scale ‘allostatic-interoceptive network’ has been shown to link some subcortical structures with cortical hubs overlapping the DMN and salience network [46].

These value-related and interoceptive processes may also interact with memory-based cognitive processes [47], including medial temporal and posterior medial regions [48], which are also subcomponents of the DMN. These cognitive systems may serve as contextual priors that shape interoceptive predictions and value computations. For example, recalling past bodily responses to certain stimuli (e.g. food, music, etc.) can bias their predicted interoceptive consequences and decisions [49,50]. Conversely, value-related and interoceptive signals may guide the retrieval and updating of self-related memories [51], suggesting bidirectional interactions between embodied and cognitive self-processing. Therefore, understanding DMN function in self-relevance processing requires an integrative, systems-level perspective that bridges conventional self-related brain networks with the interoceptive and homeostatic architectures of the brainstem, hypothalamus, and subcortical and cortical regions such as striatum, amygdala, and insula.

Finally, we propose that self-relevance processing can be understood through a concept of ‘affective maps,’

Box 1 Key terminologies and their integration for an embodied view of self-relevance.

Concepts	Definition
Interoception	The process of sensing, interpreting, and integrating internal physiological signals originating inside the body, such as heart rate, blood pressure, glucose, and oxygen levels. It provides ongoing information about the internal bodily state at both conscious and nonconscious levels, supporting the perception and regulation of the internal bodily state.
Internal bodily state	The state comprising internal physiological variables that reflect the body's internal milieu. It can be conceptualized as an internal state space, whose dimensions correspond to these variables, with a viability zone defining the range compatible with survival. Outside this zone, the organism is unable to sustain life.
Homeostasis	A self-regulating process by which the body maintains the stability of its internal states, keeping them within a viability zone despite fluctuations in the external environment.
Set point	The target value or optimal range of internal physiological variables. Deviations from the set point trigger homeostatic regulatory mechanisms that act to restore these variables toward the set point. Although useful for explaining homeostasis, the set point is a latent, unobservable construct that is not static but dynamically adjusts in response to internal and external contexts.
Reward	In reinforcement learning, reward is a signal provided by the environment that guides an agent to maximize cumulative reward over time. For living organisms, survival can be regarded as the primary reward, rooted in the homeostasis of the internal bodily state. Within the homeostatic reinforcement learning framework, deviations from a homeostatic set point can serve as a basis for generating a reward signal. In this sense, reward signals originate from the internal environment, suggesting that all rewards are fundamentally internal and reflect an organism's internal state.
Value	In reinforcement learning, value refers to the expected cumulative reward an agent can obtain from a given state or action. From our embodied perspective, value can be interpreted as the predicted long-term impact of a stimulus or action on the organism's internal state. It reflects how well an action is expected to restore or maintain internal stability, positioning value estimation as a form of interoceptive forecasting.

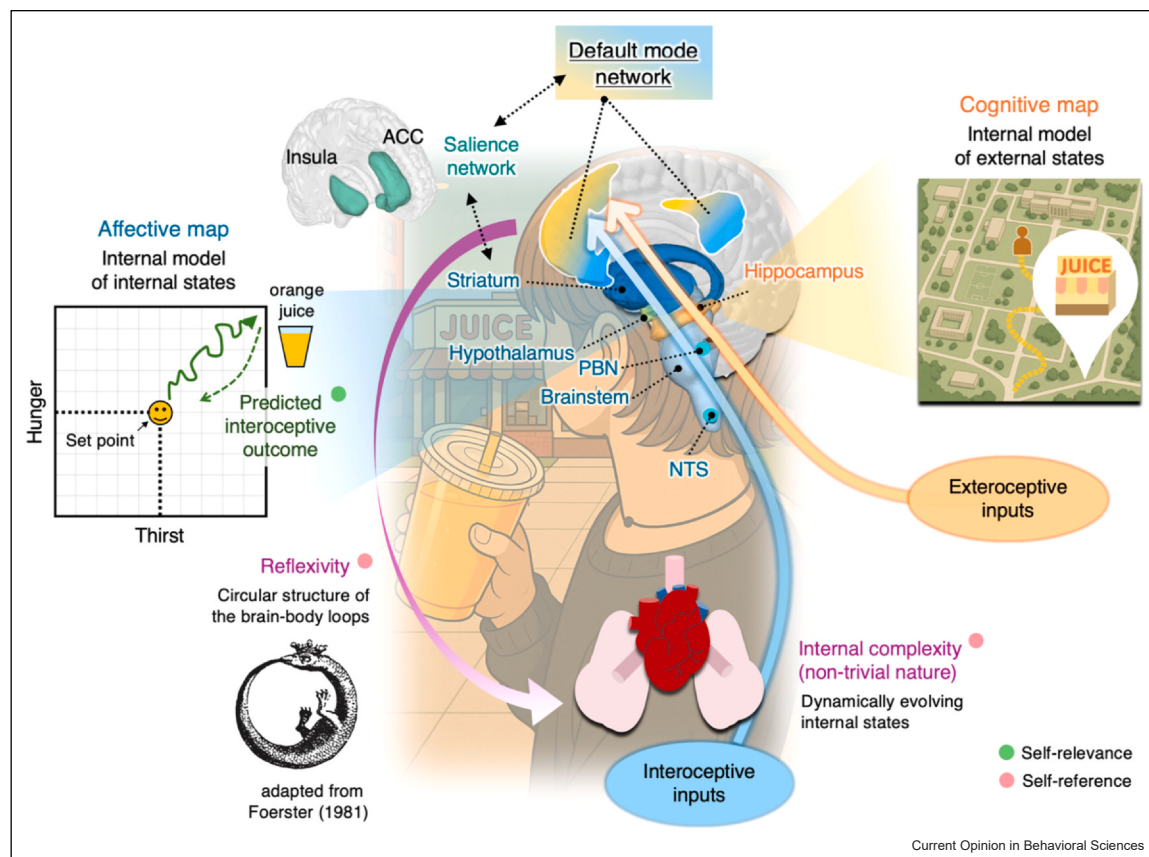


Integration of key concepts. This schematic illustrates how key concepts from reinforcement learning (RL), homeostasis, and interoception are integrated within an embodied framework of self-relevance. The agent interacts within both an external environment (e.g. a juice stand) and an internal environment (i.e. internal bodily state) that comprises internal physiological variables such as hunger and thirst. Homeostasis is maintained by regulating the internal state variables around a set point within a viability zone that defines survival. Deviations from the set point generate reward signals, which guide decisions and actions aimed at reducing the distance from the homeostatic set point. Through interoceptive inputs, the agent receives partial information about its internal state and uses it to build an internal model of the internal environment. Based on this model, the agent predicts interoceptive consequences of external stimuli or events by simulating its internal states. The prediction of interoceptive outcomes is analogous to value estimation in the RL context and serves as a basis for evaluating self-relevance..

positioned in parallel with the well-established notion of cognitive maps (Figure 2). In neuroscience, cognitive maps refer to internal models that represent spatial relationships and transition structures in the external environment [52]. In parallel, affective maps can be defined as internal models that capture the transition structures and dynamics within the internal environment. If we adopt an agent-as-a-state-space view [53], the affective map can be understood as representing an individual's position and trajectory within the internal

state space, which can then be used to compute distance from a homeostatic set-point. Recent studies have extended the role of cognitive maps beyond spatial domains, suggesting that they support the organization of abstract, generalizable knowledge structures across diverse domains of experience [54]; nevertheless, they primarily support epistemic representations of the external world. In contrast, affective maps may support the abstraction and generalization of pragmatic representations of the internal world.

Figure 2



Affective maps as internal models of the internal environment. This figure illustrates the proposed concept of affective maps as internal models of the internal environment, positioned in parallel with cognitive maps, which serve as internal models of the external environment. The cognitive maps (right, orange) support the representation of spatial and contextual relationships and transition structures in the external world based on exteroceptive inputs, primarily mediated by the hippocampus-DMN system. In contrast, affective maps (left, blue) model internal bodily states by representing transition structures and dynamics within internal state space, mediated by the striatum-DMN system. For example, an individual may simulate the Euclidean distance between their current and target locations (e.g. a juice stand) based on the cognitive map. In parallel, the individual may simulate the interoceptive consequences of drinking orange juice, represented as a return (green dashed line) from a deviation (green solid line) to a homeostatic set-point (smiley face) in internal state space. These predicted long-term interoceptive consequences render the orange juice self-relevant (green dot). This internal state modeling involves interoceptive inference and engages a distributed network that includes the DMN, striatum, hypothalamus, brainstem nuclei (e.g. nucleus tractus solitarius [NTS], parabrachial nucleus [PBN]), and the salience network (e.g. insula and anterior cingulate cortex [ACC]). Two key features of self-referential processing are embedded in this system (pink dots): 1) reflexivity, reflecting the circular structure of the brain-body interactions, and 2) internal complexity, capturing the nontrivial, dynamically evolving nature of internal states. The ouroboros-like diagram (bottom left) symbolizes the principle of reflexivity — a circular structure in which the brain and body co-regulate each other. This cybernetic view highlights second-order self-referentiality, wherein the system includes itself in its own modeling and control. Together, these components support a distributed, embodied self-model, positioning the DMN as a central node in constructing and regulating selfhood through interoceptive and affective processes deeply grounded in embodiment. (Background image in this figure was generated using a generative AI tool.). The ouroboros-like diagram (bottom left) is adapted from Foerster [64].

This ‘internal world’ model — an internal model of the internal environment — is likely to be encoded primarily in the striatum and the DMN subregions such as the vmPFC and PCC [55,56], along with the brain regions related to internal bodily states. Particularly, the ventral striatum — which consistently coactivates with the vmPFC and PCC — may support reward computation and valuation by representing and simulating the internal state space through the integration of interoceptive signals and the prediction of their future trajectories. In contrast, the dorsal striatum — functionally connected with dorsomedial and lateral prefrontal cortices as well as motor-related regions — may contribute more to estimating the interoceptive consequences of actions by simulating transitions between internal states [42,57–59]. This striatum-DMN system may also interact with the hippocampus-DMN system to give rise to value representations and support self-relevance assessment and value-based decision-making [49,60]. This discussion can be extended to encompass the concept of cognitive schemas [61,62], and to suggest a corresponding concept of affective schemas, which describe embodied, neurocognitive templates integrating interoceptive signals, value representations, and affective maps into structured regularities that guide prediction, regulation, and self-related processing.

Embodying self-reference: a cybernetic account

Another well-known aspect of DMN function is its involvement in self-referential processing, which can also be viewed from the embodied perspective. Most tasks targeting self-referential processing in cognitive neuroscience have emphasized its conceptual and cognitive dimensions, such as self-description, self-trait judgment, or autobiographical memory retrieval tasks [3,63]. Because such tasks focus on probing self-referential processing by having participants reflect on their traits and past experiences, self-referential processing in neuroscience typically refers to the subjective and phenomenal aspects of self-reflective or introspective thought. However, adopting a broader definition of self-referential processing — for example, monitoring and acting upon itself [64] — enables incorporating bodily signals into the self-referential process. From this perspective, interoception can be conceptualized as ‘monitoring’ the systems-level information of the internal milieu, while autonomic regulation represents the ‘acting upon itself’ component [65]. Notably, as mentioned above, DMN regions, particularly the medial prefrontal cortex, also participate in visceromotor control and autonomic regulation [43,45].

This embodied view of self-referential processing can find historical resonance in the field of cybernetics, the study of autonomous control and communications in

systems, particularly in second-order cybernetics [64]. While first-order cybernetics focused on negative feedback [66], second-order cybernetics extends this focus to systems that observe, regulate, and modify themselves — that is, self-referential systems. Negative feedback, which stabilizes a variable by counteracting deviations, represents a rudimentary form of self-regulation and is found in both living and non-living systems. For example, a thermostat maintains room temperature near a set-point, and even simple anticipatory behaviors — like a cat predicting a mouse’s path — can involve predictive negative feedback loops [67]. However, these processes, while adaptive, do not by themselves constitute self-referential systems in the full sense. What makes self-referential systems distinct is not merely their ability to maintain stability, but their capacity to include themselves in the loop of regulation — to observe and modify their own operations.

Self-referentiality in second-order cybernetics stresses reflexivity (or circularity) where the observer is not separate from the system it controls — it is embedded within it. This circular structure, where the system includes a model of itself or influences itself through self-regulation, is referred to as ‘reflexivity’ [64]. This is often phrased as “the cybernetics of cybernetics” or “observing systems,” highlighting that the act of observation becomes part of the system being controlled. In humans, this means that the brain participates in regulating its own body, creating inherently self-referential loops (Figure 2). Second-order cybernetics also emphasizes the ‘nontrivial’ nature of self-referential systems characterized by internal complexity. One of the pioneers of second-order cybernetics, Heinz von Foerster’s idea of ‘nontrivial machines’ [64] describes systems that have an internal state that dynamically changes over time, so the same input might yield different outputs at different times. He suggested that living organisms are nontrivial machines, incorporating feedback in such a way that the system actively changes itself as it interacts with the world. Throughout evolution, even prior to the emergence of the brain, organisms exhibited a self-referential nature, enabling systems to monitor and regulate themselves in relation to their internal and external environments, as corroborated by Jakob von Uexküll’s notion of “the supra-machine regulation as a specific characteristic of life” [68].

Importantly, the DMN functions can be interpreted through the lens of embodied self-referentiality — namely, reflexivity and nontriviality — offering a promising direction for reconceptualizing its role beyond its cognitive aspects. First, the principle of reflexivity is deeply embedded in the DMN’s architecture and functional roles. Rather than serving as a detached cognitive monitor, the DMN can be viewed as an integral component of the brain–body system, a tightly coupled

whole in which the brain and body co-regulate each other. DMN activity both reflects and shapes internal physiological states by participating in the bidirectional loops: sensing bodily signals such as interoceptive and autonomic inputs, while also generating descending regulatory outputs that influence bodily tone and homeostasis [43,45]. This integrative role can be further elaborated by considering the DMN's relationship with the central autonomic network (CAN) and other systems involved in autonomic regulation [69–71]. In this sense, the DMN does not merely represent the self but actively participates in constructing and adjusting the body-in-context — a dynamic integration of the bodily self and environmental demands.

Second, the nontrivial and dynamic nature of the DMN aligns with its proposed role as an embodied internal model. Its function is not fixed or purely reactive; rather, it encodes prior state history, predictions, and self-relevant contexts that continuously evolve [72,73]. Just as von Foerster's nontrivial machine produces different outputs for the same inputs depending on its history, the DMN provides a dynamic internal context that guides interpretation, affective tone, and regulatory responses [74]. Crucially, this internal model does not solely refer to the brain or the DMN; the body itself also constitutes an internal model, through its role in constraining and informing perception, emotion, and action [75]. From this perspective, the DMN and the body together instantiate a distributed, embodied self-model, one that is enacted and sustained through recursive sensing and regulation.

Conclusion

In this paper, we propose a conceptual framework for understanding the DMN through the lens of embodiment, reframing traditional cognitive accounts of self-related processing to include bodily dimensions. We reconceptualized self-relevance processing as the prediction of long-term interoceptive consequences, which could be understood as value estimation. This reframing highlights the DMN's role as an internal model of the internal environment, conceptualized as affective maps. We further embodied self-referential processing by integrating key concepts from second-order cybernetics, emphasizing the DMN's role in the reflexive, nontrivial operations of the brain–body system. Future work should adopt an integrative, systems-level perspective to investigate the DMN's dynamic interactions with subcortical, visceromotor, and interoceptive systems, including the brainstem, hypothalamus, striatum, and salience network. There is also a pressing need to develop fMRI paradigms specifically designed to probe the embodied dimensions of self-related processing. For example, future studies could extend beyond currently available measures of interoceptive sensitivity or

gut–brain coupling by targeting simulated (or actual) transitions within an internal state space, engaging internal models of internal bodily states and interoceptive inference and regulation. Taken together, our embodied perspective offers an extended view of DMN function in supporting selfhood as deeply grounded in bodily processes. This perspective holds important implications for understanding the brain–body connection and may inform clinical approaches to disorders of self and embodiment.

CRedit authorship contribution statement

Hong Ji Kim: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Jeong In Lee:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Choong-Wan Woo:** Conceptualization, Funding acquisition, Project administration, Visualization, Writing – original draft, Writing – review & editing.

Data Availability

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

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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