Interoceptive inference: homeostasis and decision-making

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In a recent article in TICS [1], Seth makes the compelling claim that interoceptive inference (i.e., the approximate Bayesian inference about internal bodily states) underlies body ownership and selfhood. In this letter, we argue that the significance of interoceptive inference extends beyond this. In particular, we emphasise the role of interoceptive inference in both homeostasis and allostatic (i.e., the process of achieving homeostasis) [2], and how this role grounds decision-making and motivated behaviour, when contextualised in the setting of hierarchical active inference.

To persist over time, organisms must restrict themselves to a small subset of possible biophysical states [3]. Under the free energy principle [3], this homeostasis arises because organisms minimise surprise, conditioned on their model of the world. In other words, they seek out the states they expect to occupy, where these ‘familiar’ states are innately valuable [3]. There are two ways to achieve this: first, through homoeostatic control of the internal milieu of the agent via autonomic responses [1,4,5]; and, second, through allostatic actions on the external world [2,3] (Figure 1). Consider an agent whose blood sugar level falls below a certain threshold to an undesirable or surprising level. In this situation, homeostasis can be maintained through the metabolism of bodily fat stores (when food is not available), or consummatory behaviour (when food is available). In real-life situations, both autonomic reflexes and somatic reflexes conspire to maintain homeostasis. Crucially, both processes can also be explained as surprise or prediction-error minimisation, albeit acting through different mechanisms. We argue that interoceptive inference is not only involved in the first (homeostatic) process, but also participates in the latter (allostatic) process by informing value-based choices about the internal state of the body.

We believe this notion can explain the key role of the insular cortex in decision-making [6]. A popular taxonomy considers the representation of internal and external states as a prelude to decision-making, followed by valuation, action selection, outcome evaluation, and, finally, learning and information updating [7]. The insular cortex is widely held to encode and represent interoceptive information [1,4,5] and, in so doing, acts to contextualise choice behaviour by informing other neural systems about the internal state of the body. In other words, the insula computes a ‘state’ variable of the internal world of the agent and passes it to other neural systems that carry out other computations in decision-making.

Naturally, this perspective also enables us to sketch a potential relation between the insula and the ventromedial prefrontal cortex (vmPFC), a region crucial for valuation [8,9]. The vmPFC receives both interoceptive and exteroceptive information and is strongly coupled to the hippocampus, giving it access to mnemonic information and model-based planning [9]. This anatomical affiliation enables it to integrate interoceptive information conveyed by the insula with exteroceptive, and other types of information, to generate amodal value representations that

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**Figure 1.** Illustration of the role of interoceptive inference in homeostasis and decision-making. A change in x, one of internal states of the body, away from an expected (unsurprising) bodily state is registered by the insular cortex. (Black: inferred current value. Green: expected value. Broken lines: full probability distribution. Unbroken lines: mean.) This deviation or surprise can be reduced either homeostatically, via autonomic reflexes that resolve interoceptive prediction errors, or allostatically, via action, giving rise to motivated behaviour that resolves proprioceptive prediction errors.
drive choice behaviour or prescribe behaviour through proprioceptive predictions. This picture corresponds closely with a wide consensus as to the role of the vmPFC [8].

To conclude, we extend the notion of interoceptive inference to cover (allostatic) exteroceptive and proprioceptive decision-making processes. We propose that, in addition to representing body ownership and selfhood [1], the contribution of interoceptive inference also involves maintaining homeostasis by informing allostatic decisions about the internal state of an agent. Proposing a key role for interoception in decision-making is not new [1,4,5,10], and our proposal can be seen as placing ideas such as the ‘somatic marker hypothesis’ [10] within embodied predictive coding. However, our formal hypothesis enables us to make more specific predictions about the functional role of the insula and other brain regions. From this perspective, the links between value, homeostasis, and interoceptive inference can be disclosed within the larger setting of hierarchical active inference.

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References