

Abstract

Allostasis—the brain’s predictive regulation of bodily energy—depends critically on interoception, the sensing of internal physiological signals. This review examines how interoceptive mechanisms guide the selection of allostatic energy states, surveys the Dynamic Ecosystem Adaptation through Allostasis (DEA-A) model, and explores how allostatic load and stress reactions arise when predictive regulation falters. We highlight how modifying the inputs to interoception—ranging from metabolic cues to psychosocial signals—can recalibrate allostatic states, offering novel pathways for enhancing resilience and health.

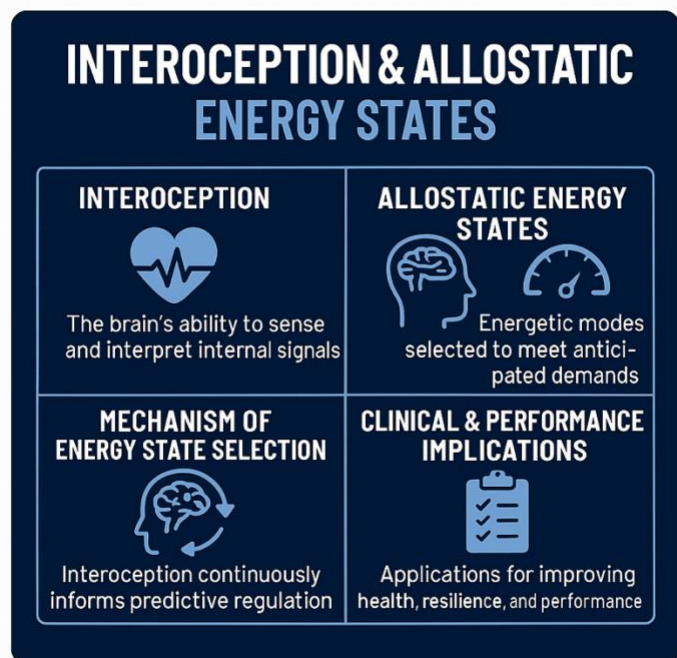
1. Introduction

Classical models of physiological regulation emphasized homeostasis, a reactive correction of disturbances to maintain internal constancy. In contrast, allostasis anticipates future demands, adjusting internal parameters proactively to optimize energy use (Sterling & Eyer, 1988; Sterling, 2012). At the heart of allostasis lies interoception—the continuous monitoring of internal signals such as heart rate, respiration, and metabolic status. By integrating interoceptive feedback with prior predictions, the brain selects the most appropriate allostatic energy state for current and upcoming challenges.

2. Mechanisms of Interoception in Allostatic Control

The EPIC Framework: The Embodied Predictive Interoception Coding (EPIC) model posits that agranular visceromotor regions (e.g., anterior insula, dorsal anterior cingulate cortex) generate top-down predictions about bodily needs, sending anticipated interoceptive signals to primary interoceptive cortex (dorsal mid-posterior insula) (Barrett & Simmons, 2015; Barrett, 2017). Prediction errors—the mismatch between predicted and actual interoceptive input—are fed back to visceromotor hubs to refine future forecasts.

Neural Substrates: Functional connectivity studies reveal a unified allostatic–interoceptive network, anchored in the default mode and salience networks, that links visceromotor hubs to interoceptive cortex and subcortical autonomic centers (Kleckner et al., 2017). This domain-general system underpins not only energy regulation but also wider cognitive and emotional functions, highlighting the inextricable link between mind and body.



3. Dynamic Ecosystem Adaptation through Allostasis

The DEA-A Model: Broc and colleagues (2024) extend allostasis beyond the individual to ecosystem adaptation, proposing the Dynamic Ecosystem Adaptation through Allostasis (DEA-A) framework. DEA-A articulates two levels:

- **Intrasystem adaptation:** how individuals and organizations dynamically allocate internal resources in response to demands.
- **Ecosystem adaptation:** how these actors, in symbiosis with their environment, co-evolve through feedback loops of resource availability and systemic change.

Integrative Feedback Processes: DEA-A emphasizes bidirectional influences: environmental stressors alter interoceptive inputs (e.g., temperature, social conflict), which in turn shape allostatic responses that modify ecosystem dynamics (e.g., community health, organizational resilience). This multilevel perspective underscores that allostasis operates within—and transforms—a larger living system.

4. Allostatic Load and Stress Reactions

Energetic Cost of Allostasis: Every allostatic adjustment consumes energy. Bobba-Alves et al. (2022) propose the Energetic Model of Allostatic Load (EMAL), showing that chronic stress induces hypermetabolism—energy expenditure above optimum—which accelerates cellular wear and promotes disease.

Experimental Evidence: Indirect calorimetry studies demonstrate that acute psychological stressors raise whole-body energy expenditure by 9–67% in humans and animals (Carroll et al., 1986; Sawai et al., 2007; Harris et al., 2006). Sustained activation of allostatic circuits—driven by persistent interoceptive mispredictions—leads to allostatic load, manifesting as cardiovascular strain, metabolic dysregulation, and impaired immunity.

5. Modulating Allostatic States via Interoceptive Inputs

Types of Interoceptive Inputs: Interoception samples a wide array of signals:

- **Metabolic cues:** blood glucose, free fatty acids
- **Cardiovascular indicators:** heart rate variability, blood pressure
- **Respiratory patterns:** tidal volume, chemosensory outputs
- **Neuroimmune factors:** cytokine levels, inflammation markers
- **Psychosocial signals:** perceived threat, social support

Each input shapes the prediction landscape of the brain, influencing which allostatic energy state is selected.

Intervention Strategies: By altering interoceptive inputs, we can steer allostatic regulation:

- **Mindfulness & Breathwork** enhance awareness of cardiac and respiratory signals, reducing prediction error and lowering allostatic load (Khalsa et al., 2009).
- **Biofeedback & Wearables** provide real-time metrics (e.g., HRV) to recalibrate autonomic predictions (Sleight et al., 1987).
- **Biologic Signaling Technologies**, such as sublingual formulations, can deliver precise molecular cues to interoceptive receptors, expediting allostatic shifts toward recovery or mobilization states.

6. Clinical and Global Health Implications

Personal Health: Improving interoceptive accuracy and managing input quality can attenuate allostatic load, reducing risk for stress-related disorders (anxiety, depression, cardiometabolic disease).

Organizational Resilience: Applying DEA-A, organizations can monitor collective “interoceptive” metrics (e.g., employee fatigue, resource utilization) to anticipate systemic stressors and adjust policies proactively.

Ecosystem Well-Being: At the global level, integrating allostatic principles encourages interventions that align environmental policies with human and ecological energetic constraints—promoting sustainable health and development.

7. Conclusion

Interoception is the pivotal mechanism by which the brain predictively regulates energy through allostasis. The DEA-A model situates this process within a living ecosystem, revealing multiscale adaptation pathways. By understanding and modifying the inputs to interoception—metabolic, cardiovascular, respiratory, immune, and psychosocial—we can recalibrate allostatic states, mitigate allostatic load, and foster resilience across individuals, organizations, and ecosystems.

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