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DEVELOPMENTAL MEMORY AS A MISSING LINK IN THE ARCHITECTURE OF BIOLOGICAL SELF-REGULATION

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ABSTRACT

Background. Biological self-regulation is conventionally modeled in terms of present anatomy and feedback control. We propose that self-regulation may also depend upon retained information about prior organization a property we term developmental memory. Developmental memory acts as a missing link in biological self-regulation by serving as the experiential foundation that shapes neural architecture. It transforms primitive, gene-driven reflex pathways into complex, top-down regulatory systems like the **prefrontal cortex.** Experience-Dependent Synaptic Pruning: Early life experiences dictate which neural connections are strengthened or pruned away. The medial prefrontal cortex (mPFC), a critical hub for executive functioning and cognitive flexibility, relies on this prolonged maturation. **Hypothesis.** We hypothesize that living systems preserve traces of developmental organization through genetic, epigenetic, structural, mechanical, neural, fascial, and rhythmic continuities, and that self-regulation may represent the ongoing expression of this retained organization acting within present physiological conditions. We examine the cranio-cervical-hyoid (CCH) complex as a visible convergence zone where these continuities may be observed and tested. **Framework.** We propose a four-level hierarchy: developmental memory gives rise to visceral–cervical coupling, which is monitored through temporal sensing, which in turn enables biological self-regulation. Visceral–cervical coupling is defined as a proposed anatomical and physiological network linking the visceral column, diaphragm, anterior longitudinal ligament (ALL), esophagus, infrahyoid system, hyoid, cervical fascia, and cranio-cervical structures. Temporal sensing is defined as a pre-conscious capacity by which living systems detect and maintain phase relationships among interacting physiological rhythms, distinct from conscious time perception, interoception, and proprioception. **Predictions.** The framework yields testable predictions linking CCH structural integrity to respiratory-postural coupling, hyoid position and cervical alignment to heart rate variability coherence, and cervical proprioceptive acuity to physiological synchronization, with impaired temporal coherence anticipated in dysphagia, temporomandibular, chronic pain, dysautonomia, and disordered breathing populations. **Significance.** This framework reframes self-regulation as the adaptation of retained developmental organization to present conditions, using the neck not as the theory itself but as the anatomical case study through which the organizing principle becomes observable.

KEYWORDS: *developmental memory; visceral–cervical coupling; temporal sensing; biological self-regulation; cranio-cervical-hyoid complex; anterior longitudinal ligament; hyoid; fascial continuity; embryological migration; respiratory–postural coupling.*

Core Concept

- **Developmental memory** refers to the way early experiences and biological signals are encoded into lasting regulatory patterns.
- It integrates **genetic, epigenetic, and neurobiological processes** into a stable framework that guides self-regulation across life stages.
- This memory is not just cognitive—it includes **autonomic, metabolic, and neuroendocrine imprints** that shape how the body maintains balance (homeostasis and allostasis).

Developmental memory is increasingly seen as a crucial "missing link" in how biological systems achieve self-regulation, bridging genetic programming, neural maturation, and adaptive

behavior. It provides continuity across sensitive developmental periods, allowing the nervous system to stabilize regulatory functions while remaining flexible to environmental input.

Framework	Focus	Contribution to Self-Regulation
Ontogenetic Clock	Brainstem–cortex synchrony	Explains sensitive developmental windows for autonomic balance
Hierarchical-Circular Model	Multi-level biological adaptation	Shows how disrupted memory loops cause neurodevelopmental disorders
Autobiographical Memory	Episodic & identity-based	Links personal continuity to behavioral regulation

Challenges & Risks

- **Clinical heterogeneity**: Disrupted developmental memory may explain why disorders like ADHD or autism vary so widely in presentation.
- **Sensitive periods**: Interventions must align with developmental windows; missing them can lead to maladaptive regulatory states.
- **False memory risks**: At the autobiographical level, distortions can destabilize self-regulation and identity.

Mechanisms Linking Memory and Self-Regulation

- **Ontogenetic self-regulation clock**: A developmental timeline where brainstem-autonomic synchrony gradually comes under cortical control. This "clock" encodes regulatory milestones into memory traces.
- **Hierarchical-circular biological memory**: A systems model showing how signals (genetic, stress, immune) become embedded and propagate circularly, creating stable regulatory states.
- **Autobiographical memory**: At higher levels, episodic memory interlocks with identity, reinforcing self-regulation through narrative continuity.

Introduction: The Problem of Continuity After Separation

Living systems are thermodynamically open but organizationally closed. Their material components turn over continuously, yet a material-independent property — organization — persists. The central question this raises is how organization is established, maintained, and recovered across time, particularly when the structures embodying that organization undergo migration, differentiation, and spatial separation during development. During embryological development, organs that originate in proximity migrate to distant final positions. The heart, the thymus, the gonads, and the digestive viscera all descend or translocate from their sites of origin. Yet these structures do not become independent of their developmental relationships. They remain connected through neural pathways, vascular pedicles, fascial planes, and mechanical continuities that trace the route of their migration. The phrenic nerve descending from the cervical spine to the diaphragm, the vagus accompanying the gut, and the testicular vessels arising high on the posterior abdominal wall are each a record of where a structure began, preserved within where it ended.

We propose that this preservation is not incidental but functionally significant. We term it developmental memory: the persistence of organizational information across development, differentiation, migration, and adaptation. This central proposition may be stated directly.

Self-regulation may not simply maintain organization; it may be the ongoing expression of retained developmental organization adapting to present physiological conditions.

This paper develops that proposition. We do not claim to have proven a missing link. We propose a framework, define its terms, locate it within existing theory, and specify the predictions by which it may be tested. We use the cranio-cervical-hyoid (CCH) complex as the anatomical case study because it is the most visible convergence zone in which developmental memory, visceral–cervical coupling, and temporal sensing may be simultaneously observed. The neck is the case study; developmental memory is the organizing principle.

Existing Models of Self-Regulation

Several established frameworks describe how living systems maintain themselves, each capturing part of the phenomenon while leaving the question of retained organization incompletely addressed.

Autopoiesis and organizational closure

The theory of autopoiesis describes living systems as networks of processes that continuously produce and regenerate the components from which they are made, thereby maintaining the organization that defines them as a unity. Relational and organizational accounts similarly emphasize that living systems are defined by closure of their constitutive processes rather than by their material substrate. These accounts establish that organization is the invariant of life, but they characterize organization as a present-tense property maintained in the moment, with less attention to how prior organizational states are retained and expressed.

Allostasis and predictive regulation

Allostatic models describe regulation as the achievement of stability through change, in which the organism anticipates demand and adjusts set points predictively rather than defending fixed values. Active inference and free-energy formulations extend this by modeling the organism as minimizing the discrepancy between expected and sensed states. These frameworks foreground prediction and anticipation, which are temporal in nature, but they typically locate the relevant priors in neural and statistical models rather than in retained structural and developmental organization.

Interoception and the sensing of internal state

The science of interoception describes how the organism senses, integrates, and regulates signals arising within the body. Interoception establishes that internal sensory information is continuously monitored and is central to regulation and affect. We build upon this literature while distinguishing our proposed construct of temporal sensing, which concerns the detection of phase relationships among rhythms rather than the magnitude of any single internal signal.

Temporal Sensing

We define *temporal sensing* as a pre-conscious capacity by which living systems detect and maintain phase relationships among interacting physiological rhythms. It is distinct from conscious time perception, which concerns the subjective experience of duration; from interoception, which concerns the sensing of internal bodily states; and from proprioception, which concerns the sensing of body position and movement. Temporal sensing concerns none of these directly. It concerns whether processes are in phase: whether a cycle has completed, whether two rhythms are synchronized, whether the window for a coordinated action is open or closed.

Many essential biological processes breathing, heartbeat, gait, swallowing, peristalsis, vocalization, and postural stabilization depend on cyclic or wave-like patterns that must begin, continue, adjust, complete, and transition at appropriate times relative to one another. Respiratory sinus arrhythmia, the coupling of heart rate to the respiratory cycle, is a familiar instance of two rhythms held in phase. Locomotor-respiratory coupling is another. We propose that the maintenance of such phase relationships requires a sensing capacity, and that this capacity is logically and physiologically prior to motor correction: the organism must detect that phase has drifted before it can act to restore it.

We hypothesize that temporal sensing is the mechanism by which retained developmental organization is continuously compared against present physiological conditions. Where the phase relationships predicted by retained organization and those present in current function diverge, the organism experiences a regulable mismatch. Self-regulation, on this view, is the process of reducing that mismatch — not toward a fixed set point, but toward the phase coherence implied by the system's retained organization.

Developmental Memory and Retained Organization

Developmental memory is not the recollection of past events but the persistence of organizational information across time. Through development, differentiation, migration, and generation after generation of biological continuity, living systems preserve traces of prior organization. Self-regulation may therefore represent the ongoing expression of retained developmental information acting within present physiological conditions.

This does not imply cognitive memory at the tissue level. There is no claim of recollection, awareness, or representation within tissue. Developmental memory refers to retained organizational relationships embodied within genetic programs, developmental pathways, anatomical continuities, physiological rhythms, mechanical loading histories, and adaptive regulatory networks. It is memory in the sense that a river retains the memory of its watershed, or a folded protein retains the memory of its sequence — organizational information carried forward in structure, not in cognition. We use the term advisedly and restrict it throughout to this structural sense; no claim of awareness, intentionality, or representation at the level of tissue is intended or implied.

The developmental descent of the foregut provides a compelling anatomical metaphor for the persistence of structural continuity across spatially separated systems. Although organs migrate and differentiate during development, they remain connected through neural, fascial, vascular, and mechanical pathways. This continuity offers a useful conceptual model for understanding how temporally coordinated regulation may emerge across distant physiological domains.

The phenomenon generalizes well beyond the gut. The descent of the heart from the cervical region carries the phrenic and vagal relationships with it. The descent of the thymus from the third pharyngeal pouch leaves a fascial and positional trail into the mediastinum. The descent of the gonads from the high posterior abdominal wall to their final positions preserves a vascular and neural continuity that traces the entire migratory path. In each case, separation in space does not abolish organizational relationship; it preserves it in altered form. The core proposition of this paper is that such retained relationships are not merely anatomical curiosities but active participants in ongoing self-regulation.

A living system may be understood as a structure that was once connected, became separated, retains information about prior organization, and continuously attempts to reorganize itself.

This formulation poses what we regard as the central empirical question of the framework: *what information survives separation, and how does that information guide reorganization?*

Visceral–Cervical Coupling

We define *visceral–cervical coupling* as a proposed anatomical and physiological coupling network linking the visceral column, diaphragm, anterior longitudinal ligament, esophagus, infrahyoid system, hyoid, cervical fascia, and cranio-cervical structures. This network is proposed as one concrete anatomical expression of developmental memory — a continuity that persists from the embryological proximity of the foregut and pharyngeal structures to the cervical region, retained through the descent of the viscera into the thorax and abdomen.

The anterior longitudinal ligament (ALL) runs from the occiput to the sacrum along the anterior surface of the vertebral bodies, constituting the longest continuous ligamentous structure in the axial skeleton. The crura of the diaphragm attach directly to the anterior surfaces of the upper lumbar vertebrae — the right crus extending across the L2–L4 bodies and the left across L1–L3 in recent cadaveric measurement (Khadanovich et al., 2025) — placing the diaphragm in direct fibrous continuity with the ALL. Through this continuity, the rhythmic activity of respiration is transmitted as cyclic mechanical loading along the anterior spinal axis. The esophagus descends immediately anterior to this column, traversing the diaphragm at the esophageal hiatus, and the infrahyoid musculature and anterior cervical fascia continue the chain superiorly to the hyoid and cranio-cervical structures.

We propose that this network functions as a coupled mechanical and informational pathway. Respiratory-postural coupling, in which the diaphragm contributes to both ventilation and trunk stabilization, is well documented and provides direct evidence that the diaphragm participates simultaneously in visceral and postural domains. We extend this established coupling cranially, proposing that the cervical and cranio-cervical structures are mechanically and rhythmically coupled to the thoracoabdominal viscera through the continuity described above.

The Hyoid as a Myofascial Transducer

Within the visceral–cervical coupling network, the hyoid bone occupies a uniquely informative position. We propose that the hyoid functions as a sensitive myofascial transducer because it is suspended without direct bony articulation and participates simultaneously in swallowing, airway regulation, tongue mechanics, cervical posture, and visceral-cervical force transmission.

Unlike every other osseous element of the region, the hyoid articulates with no adjacent bone. Its position is determined entirely by the dynamic equilibrium of the suprahyoid musculature acting superiorly and the infrahyoid musculature acting inferiorly. Because the inferior chain is continuous with the laryngotracheal complex and, through the anterior cervical fascia, with the thoracic inlet, the hyoid registers tension transmitted from the visceral column. Because the superior chain is continuous with the mandible and skull base, changes in hyoid position propagate to craniomandibular function. The hyoid is therefore positioned to transduce visceral-cervical tension into a mechanical signal accessible to the densely innervated structures of the neck.

The Fall-Away Model

We define the *fall-away* as the persistent inferior tension bias associated with the embryological descent and migration of visceral structures from a more cranial developmental organization. As the foregut and associated viscera descend into the thorax and abdomen, the anterior visceral column comes to exert a sustained inferior load on the structures with which it retains continuity the ALL, the anterior cervical fascia, and the infrahyoid suspension of the hyoid.

We propose that this inferior bias is not transient but persistent, reflecting the retained organizational relationship between the cervical region and the descended viscera. The organism accommodates this bias through continuous compensatory postural and tensional adjustment. We hypothesize that the quality of this accommodation depends on the integrity of temporal sensing within the CCH complex: the more accurately the system can detect the phase relationships among respiratory, postural, and visceral rhythms, the more adaptively it can regulate against the inferior bias of the fall-away.

The fall-away model thus integrates the preceding constructs. Developmental migration establishes a retained organizational relationship (developmental memory); that relationship is embodied in a continuous anatomical network (visceral–cervical coupling); the network imposes a persistent mechanical bias (the fall-away); and the organism regulates against that bias through the detection of phase relationships (temporal sensing) in the service of self-regulation.

Testable Predictions

The framework yields the following testable predictions, ordered from structural to clinical:

1. Cranio-cervical-hyoid structural integrity will correlate with measures of respiratory-postural coupling.
2. Hyoid position and cervical alignment will correlate with heart rate variability and respiratory sinus arrhythmia coherence.
3. Cervical proprioceptive acuity will predict the degree of respiratory-postural synchronization.
4. Populations characterized by dysphagia, temporomandibular dysfunction, chronic pain, dysautonomia, and disordered breathing may show impaired temporal coherence across physiological rhythms.
5. Interventions that improve cranio-cervical-hyoid mobility may improve physiological coherence markers.

Clinical Implications

If temporal sensing within the visceral–cervical coupling network contributes to biological self-regulation, then disorders characterized by disrupted self-regulation may share an upstream contribution from degraded coupling or temporal sensing at the CCH complex. This would suggest that the clinical assessment of conditions such as temporomandibular dysfunction, chronic neck pain, dysphagia, disordered breathing, and certain forms of autonomic dysregulation may benefit from evaluation of thoracoabdominal and visceral-cervical mechanics, not only local structures.

We emphasize that these implications are hypotheses for investigation rather than established clinical recommendations. The framework is offered to generate testable questions and to organize existing observations, not to prescribe treatment in advance of evidence.

DISCUSSION

The principal contribution of this framework is to reframe self-regulation as the ongoing expression of retained developmental organization, rather than solely as the maintenance of present-tense organization or the minimization of present-tense prediction error. This reframing situates the framework alongside autopoiesis, allostasis, active inference, and interoception, with which it is complementary rather than contradictory. Where autopoiesis emphasizes present organizational closure, the developmental memory framework adds a temporal dimension: the organization that is closed in the present carries information from the past and expresses it under present conditions.

We are careful to separate established anatomy from proposed integration. The anatomical continuities described the ALL, the diaphragmatic crura, the infrahyoid suspension of the hyoid, the fascial planes following organ migration are well documented. The respiratory-postural function of the diaphragm is well documented. What is proposed, and remains to be tested, is the integration of these elements into a single coupling network, the construct of temporal sensing as the mechanism monitoring that network, and the construct of developmental memory as the organizing principle from which the network derives. We avoid claims of direct causality where only continuity and correlation can presently be supported. Several limitations follow. The framework is at present conceptual and requires the operationalization of its central constructs into measurable variables before it can be confirmed or refuted. Temporal sensing, in particular, must be distinguished empirically from established constructs of interoception and proprioception. The predicted correlations must be tested in adequately powered samples across the relevant clinical populations. And the directionality of any observed relationships — whether degraded coupling impairs regulation or vice versa — will require longitudinal and interventional designs to establish.

CONCLUSION

We have proposed that biological self-regulation may depend upon retained information about prior organization, a property we term developmental memory. We have proposed visceral–cervical coupling as one anatomical expression of this retained organization, temporal sensing as the mechanism by which phase relationships among physiological systems are monitored and maintained, and the cranio-cervical-hyoid complex as a visible convergence zone where these principles may be observed and tested. The framework reframes self-regulation not as the maintenance of organization alone, but as the ongoing expression of retained developmental organization adapting to present physiological conditions. The neck is where this principle becomes visible; developmental memory is the principle itself. Future work should operationalize the constructs defined here and test the predictions specified, so that what is presently a framework may become a body of evidence.

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