Supplementary Material

A. Boundary and Limiting Cases in the UBCAT Framework

This section provides decision-oriented boundary cases for applying the two-axis criterion introduced in Sections 2.1–2.2. To avoid behavioral-marker inflation (e.g., equating tool-like behavior with consciousness), i list representative cases where sophisticated regulation or environment-directed modification occurs without individual-level loop closure.

A.1 Non-qualifying systems: absence of both axes *(Axis A = 0, Axis B = 0)*

Representative cases:

- **simple nerve-net organisms (e.g., Jellyfish)**
  Behavior is governed by distributed stimulus–response coupling without centralized state-dependent action selection or environment-mediated causal intervention (Feinberg & Mallatt, 2017; Mackie, 1990).
- **Simple annelids dominated by reflexive control**
  Motor outputs are triggered by local sensory inputs with minimal modulation by global internal state.
- **Humans in a persistent vegetative state (PVS)**
  Autonomic regulation and reflexive responses may persist, but the recurrent causal architecture required for self-referential control and environment-mediated problem solving is absent (Laureys, 2005; Monti et al., 2010; Owen et al., 2006) (Section 2.3.1).

Non-conscious biological systems:
Behavior In these systems, internal states may fluctuate (e.g., arousal, reflex excitability), but they do not function as self-referential variables within action selection. Environmental influence is limited to direct bodily outputs, without recruiting external objects or structures as causal intermediaries.

A.2 Boundary cases: partial satisfaction of UBCAT criteria

A.2.1 Environment-mediated intervention without self-reference

This category prevents the reductive inference that environmental manipulation or tool-like behavior entails consciousness. Under UBCAT, Axis B is satisfied only when external elements are recruited as independent causal media within a closed, state-dependent control loop. Environment-directed behavior driven by fixed action patterns or distributed colony-level control does not suffice.
(cf. Section 2.2).

UBCAT distinguishes *structural availability* from *overt execution*. Where the causal architecture for environment-mediated intervention remains intact but cannot be externalized due to motor impairment, conscious agency may still be present.

However, a purely self-referential system lacking any actual or latent capacity for environmental intervention is unlikely to be biologically realizable or evolutionarily stable. Accordingly, UBCAT treats this category as a theoretical boundary condition rather than a natural class.

A) environment-directed modification (non-qualifying) *(Axis A = 0, Axis B = 0)*

Representative cases:

- **Secreted structural materials** (e.g., spiders, silkworms, biofilm-forming microorganisms) In these systems, environmental structures (e.g., webs, cocoons, biofilms) are produced through internally generated secretions and function as extensions of endogenous production processes.
  Although such structures may profoundly shape the organism’s interaction space, the environment itself is not recruited as an *independent* causal medium. Instead, causal control remains confined to internal production and release mechanisms, consistent with endocrine-only environmental interaction (cf. Grassé, 1959) (cf. Section 2.2.2).
- **Social insects operating via stigmergic coordination** (e.g., ants, termites, some bees) External materials are manipulated in response to pheromonal cues, with causal control distributed at the colony level rather than closed within the individual organism. While the colony may exhibit sophisticated environmental regulation, individual agents lack self-referential causal control. Because the effective control loop is not closed at the individual level but distributed across the colony and its stigmergic traces, Axis B is not satisfied under UBCAT (Grassé, 1959).

B) Extra-bodily causal interaction (qualifying condition) *(Axis A = 0, Axis B = 1)*

Representative cases:

- **Burrowing Construction- or object-manipulating insects using external materials** (e.g., caddisfly larvae, dung beetles)
  These organisms recruit external environmental materials (e.g., sand, debris, dung) and manipulate them in a goal-directed manner. Such behaviors satisfy the criterion of extra-bodily causal interaction, insofar as external objects function as independent causal media (Shumaker et al., 2011; St Amant & Horton, 2008).
  However, action selection appears to be governed primarily by fixed action patterns or context-bound sensorimotor rules, with limited evidence that internally modeled bodily or affective states are treated as self-attributed causal variables.
- **Human infants prior to the emergence of minimal causal agency**
  As discussed in Section 4.1, early infants interact with external objects and caregivers, yet their behavior remains dominated by reflexive and proto-regulatory mechanisms. Internal states modulate behavior, but do not yet function as explicitly self-attributed variables (Oostenbroek et al., 2016; Rochat, 2003) governing environment-mediated causal problem solving (see Supplementary Material D).

Functional agency without conscious agency:
These organisms actively modify or manipulate the environment, often in adaptive and structured ways. However, action selection is driven primarily by fixed action patterns, local sensory triggers, or distributed causal mechanisms. Internal states do not function as self-attributed causal variables governing goal selection or outcome evaluation.

A.2.2 Self-referential processing without environmental intervention *(Axis A = 1, Axis B = 0)*

This category represents a limiting rather than a robust biological case.

Representative cases

- **Humans with complete locked-in syndrome or extreme total paralysis**
  Neural architectures supporting self-referential causal control may be preserved despite the near-total loss of motor output (Demertzi et al., 2015; Laureys et al., 2006) (cf. Section 2.3.1).

A purely self-referential system without any form of environmental intervention is unlikely to be biologically realizable.

A.3 Full satisfaction of UBCAT criteria

(Axis A = 1, Axis B = 1)

Representative cases:

- **Adult humans**
  Internal bodily and cognitive states function as self-attributed variables guiding state-dependent intervention in both internal regulation and external environment manipulation.
- **Octopuses**
  Flexible object manipulation integrates internal state, interaction history, and anticipated outcomes within a closed causal loop (Birch et al., 2020; Godfrey-Smith, 2016; Mather, 2008).
- **Some mammals and birds (e.g., dolphins, corvids, magpies)**
  Goal-directed object use and state-dependent behavioral regulation support environment-mediated causal problem solving (Emery & Clayton, 2004; Prior et al., 2008).

Conscious Agents:
In these systems, internal states are explicitly incorporated into action selection as self-attributed causal variables. External objects are recruited as independent causal media, and action outcomes feed back into internal state regulation, closing the causal loop. (cf. Section 2.4.2 and 4.5).

A.4 Social responsiveness and apparent emotional interaction

A frequent source of confusion concerns organisms that appear capable of emotional or social interaction with humans despite failing to meet UBCAT's criteria for consciousness.

Many non-conscious or boundary systems can:

- Discriminate individual humans via odor, movement, or handling style
- Exhibit conditioned affiliative or avoidance behaviors
- Show stabilization or agitation in response to specific caregivers

These phenomena reflect state-sensitive conditioning, sensory discrimination, or endocrine-driven modulation rather than self-referential causal agency.

Representative case: Reptiles
Reptiles may discriminate individual human handlers via odor, tactile, or visual cues, appearing to

engage in emotional interaction (Davis & Burghardt, 2011). However, such behaviors arise from sophisticated associative conditioning and state-dependent response patterns rather than self-attributed affective regulation (Key, 2016). Even instances of social learning (Wilkinson et al., 2010) or play-like behaviors (Burghardt, 2015)reflect the optimization of sensorimotor loops and environmental prediction, failing to satisfy the requirement for a closed, self-referential causal architecture (cf. Feinberg and Mallatt, 2017). Stimulus discrimination is present, but the environment is not recruited as an independent causal medium within a self-modeled regulation regime.

This distinction allows UBCAT to acknowledge the richness of animal behavior without inflating the definition of consciousness or projecting human-like experiential structures onto systems lacking the requisite causal architecture.

A.5 Conceptual role of boundary cases

The inclusion of boundary and limiting cases serves three core functions within UBCAT:

- It prevents reductive equations such as tool use = consciousness.
- It accommodates socially rich yet non-conscious behavior without denial or anthropomorphic projection.
- It clarifies that consciousness, under UBCAT, is a property of closed, self-referential causal organization, not of behavioral complexity alone.

B. Levels of Self–Non-self Differentiation: From Cellular Immunity to Neurocognitive Development

This section disambiguates two uses of “self”. (i) cellular self–non-self discrimination mechanisms that support viability (e.g., immune tolerance and responsiveness), and (ii) neurocognitive self–other differentiation that emerges through developmental integration of perception, action, and regulation. The former is a non-conscious, molecular–cellular operation. The latter concerns subject-level organization relevant to agency and, later, explicit self-related cognition. Treating them as equivalent invites category errors.

At the cellular level, self–non-self differentiation is a fundamental biological function that operates independently of consciousness. Many cells express molecular surface features (such as cell-type–specific membrane proteins and glycocalyx patterns) that support the discrimination of endogenous components from exogenous entities (Pradeu & Carosella, 2006). For an illustrative example, the immune system provides a particularly explicit instantiation of this capacity. Adaptive immune cells (e.g., T cells, and B cells) undergo selection processes that eliminate self-reactive variants while preserving responsiveness to non-self antigens (Pradeu & Carosella, 2006). These mechanisms serve survival and homeostatic regulation, and they do not entail representation, awareness, or attribution (Ader & Cohen, 1975; Pradeu & Carosella, 2006).

By contrast, self–other differentiation at the level of neurocognitive development involves a distinct class of mechanisms and functions. Rather than relying on biochemical recognition, neurocognitive differentiation depends on multisensory integration, plasticity, and distributed functional networks (e.g., limbic and associative cortical systems) (Damasio, 2010; Fair et al., 2009; Johnson, 2001; Legrand, 2006). These processes support the formation of internal representations, the regulation of affective and social behavior, and, at later stages, the emergence of explicit self-related cognition (Damasio, 2010; Mundy & Newell, 2007).

The critical point is that although both domains employ the terminology of "self" and "non-self," they refer to different levels of organization and different explanatory targets. Cellular self–non-self discrimination is necessary for biological survival, but it does not constitute a precursor of conscious selfhood (Pradeu & Carosella, 2006). Neurocognitive self–other differentiation, in contrast, presupposes developmental integration across multiple sensory, affective, and regulatory systems and unfolds over extended postnatal timescales (Damasio, 2010; Fair et al., 2009; Johnson, 2001).

To clarify these distinctions, Table S1 summarizes key differences between self–non-self differentiation at the cellular level and self–other differentiation in neurocognitive development.

Table S1. **Comparison of Self / Non-self Differentiation Across Biological Levels**

Dimension	Cellular Level (Self / Non-self)	Neurocognitive Development (Self / Other)
Functional focus	Survival and homeostasis (immune defense) (Pradeu & Carosella, 2006)	Self-recognition, social interaction, and consciousness (Damasio, 2010; Mundy & Newell, 2007)
Core mechanisms	Membrane markers (e.g., MHC, glycocalyx); antigen–antibody interactions (Pradeu & Carosella, 2006); elimination of self-reactive cells	Sensory integration; synaptic plasticity (LTP/LTD); large-scale functional networks (e.g., hippocampus–amygdala–PFC) (Damasio, 2010; Fair et al., 2009; Johnson, 2001)
Mode of representation	Biochemical and molecular recognition (Pradeu & Carosella, 2006)	Neural circuits and cognitive representations (Damasio, 2010)
Functional outcome	Maintenance of a viable biological system and exclusion of external threats (Pradeu & Carosella, 2006)	Formation of a subject-level self distinct from others
Limitations	No representational or experiential self (Pradeu & Carosella, 2006)	Requires developmental integration beyond basic survival functions (Fair et al., 2009; Johnson, 2001)

In summary, self–non-self differentiation is not a unitary phenomenon but a level-dependent construct. While molecular self-recognition is a prerequisite for biological viability, the forms of self–other differentiation relevant to consciousness research arise only at higher levels of neural organization and developmental integration (Damasio, 2010; Hepper, 1991; Rochat, 2003). Accordingly, cellular self–non-self mechanisms are prerequisites for biological viability, but they do not constitute precursors of experiential selfhood. This distinction provides a conceptual foundation for the use of the term self–other throughout the main text and its supplementary materials.

C. Regulation Before Prediction: Cellular Foundations of a Scale-Invariant Organizing Principle

C.1 Regulation as the Primitive Biological Operation

In UBCAT terms, regulation specifies the minimal viability-preserving control regime that precedes any form of self-referential causal agency.

Across biological scales, from single cells to complex nervous systems, regulation constitutes the most basic form of organized activity (Sterling & Eyer, 1988). Regulation operates continuously in a state-dependent manner, adjusting internal variables in response to perturbations without invoking prediction, experience, or representation of future states (Pradeu & Carosella, 2006; Sterling, 2012). At the cellular level, membrane potentials, ion fluxes, and metabolic feedback loops regulate internal stability through local dynamics alone (Pradeu & Carosella, 2006).

Crucially, such regulatory activity does not require anticipatory computation. It operates through immediate coupling between current state variables and constraint-driven responses, ensuring viability under conditions of limited environmental complexity. This principle holds independently of nervous systems, cognition, or behavioral flexibility, indicating that regulation is not a derivative feature of prediction but its biological precursor.

C.2 Genetics, Epigenetics, and the Accumulation of Regulatory History

Genetic factors define the dynamic ranges and threshold conditions within which regulatory processes can operate. These constraints specify what forms of regulation are biologically possible, but not how regulation unfolds across time. Through repeated regulatory activity, biological systems accumulate the outcomes of past regulation.

This accumulation is expressed through epigenetic modification, long-term structural tuning, and persistent changes in signaling sensitivity. Epigenetic processes do not introduce new regulatory principles; rather, they stabilize successful regulatory trajectories across time, increasing responsiveness to recurring environmental conditions (Ciaunica et al., 2021; Lickliter, 2011). Regulatory history therefore shapes future regulatory efficiency without introducing anticipatory or representational mechanisms.

C.3 Cellular Mechanisms of Pre-Predictive Regulation

C.3.1 Distributed State Embodiment: Matter as Information

At the most fundamental biological scale, internal “state” is not centrally represented or symbolically encoded. Instead, state is distributed across the cytosol and membrane systems as a physical field of material conditions. In cellular organization, matter and information are not separable.

Core state variables include *ATP/ADP* ratios, intracellular Ca^{2+} concentration, reactive oxygen species *(ROS)*, *pH* gradients, membrane composition, and metabolite availability. These variables do not describe the state. They are the state (Damasio, 2010). Cellular responsiveness emerges from the continuous modulation of these material conditions rather than from explicit sensing or inference.

Organelles function as regulatory substrates within this distributed state architecture:

- **Mitochondria** regulate global energetic tempo via ATP production and redox signaling (Attwell & Laughlin, 2001; Lane & Martin, 2010).
- **Lysosomes** act as metabolic signaling hubs through nutrient sensing and mTOR-related pathways, implementing switches between growth-oriented and conservation-oriented modes (Perera & Zoncu, 2016).
- **Endoplasmic** reticulum governs Ca^{2+} storage and release, shaping baseline excitability across contraction, secretion, and gene expression (Berridge, 2016).
- **Nucleus** does not encode the present state but reserves future structural possibilities through transcriptional regulation based on accumulated regulatory history.

C.3.2 Integration Interfaces: From Distributed Fields to Regulatory Action

Distributed state variables are synthesized into coherent regulatory responses through multiple simultaneous integration interfaces rather than through centralized control. Four mechanisms are particularly critical:

- **Concentration Fields:**
  Continuous gradients of *ATP,* Ca^{2+}*, ROS,* and metabolites provide an analog, real-time representation of internal state.
- **Protein–Protein Interaction Networks:**
  Regulatory computation occurs probabilistically through binding affinities and interaction likelihoods rather than discrete logical operations.
- **Membrane Contact Sites (MCS):**
  Physical junctions between organelles (e.g., ER–mitochondria, ER–lysosome) serve as local integration nodes where Ca^{2+}, lipids, and signaling molecules are exchanged directly, bypassing long-distance diffusion (Scorrano et al., 2019).
- **Ion Channels as State-to-Response Transducers:**
  Ion channels compress the global cellular state into actionable outputs by converting voltage, ligand concentration, or mechanical deformation into discrete physiological responses (Laughlin & Sejnowski, 2003).

Together, these interfaces allow regulation to emerge as a temporally integrated, state-dependent process without invoking prediction or representation.

C.3.3 Organellar Coordination and Temporal Integration

Regulatory meaning does not arise from isolated molecular events but from their temporal integration. Single ion fluxes or transient molecular interactions carry no regulatory significance in isolation. Regulatory control emerges only when activity is integrated across time and space, producing stable internal states such as resting membrane potential, sustained metabolic modes, or prolonged excitability shifts.

Organellar coordination plays a central role in this integration. ER–mitochondria–lysosome coupling synchronizes energetic status, calcium signaling, and nutrient availability, while the nucleus encodes longer-term regulatory commitments. Regulation, therefore, precedes reflexes, prediction, and inference. It represents the minimal unit of biological organization capable of maintaining stability over time.

C.3.4 Regulatory Stability as the Threshold for Prediction

Prediction is not energetically or structurally free. Anticipatory computation carries significant metabolic cost (Attwell & Laughlin, 2001; Laughlin & Sejnowski, 2003) and introduces the risk of catastrophic interference when predictions fail. For this reason, biological systems do not predict early.

Prediction becomes viable only when regulatory activity has accumulated sufficient coherence and stability to support a computable state space. In the absence of such stability, anticipatory processing would destabilize rather than protect the system. Regulation must therefore reach a functional threshold before prediction becomes advantageous.

This explains why early biological systems and early developmental stages, operate exclusively within pre-predictive regimes. The absence of prediction reflects functional sufficiency, not deficit.

C.3.5 Integration Interfaces: From Distributed Fields to Regulatory Action

The regulatory-to-predictive transition is reflected in characteristic temporal scales observable in neural systems:

Table S2. **Characteristic Timescales Across Processing Levels**

Level	Timescale	Functional Role
Ion channel opening	milliseconds	State sensing
EPSP/IPSP integration	10–100 ms	Regulation
Action potential	~1 ms (event), tens of ms (patterns)	Response
Network stabilization	100–300 ms	Regulatory state
Mismatch Negativity (MMN)	**~150–250 ms**	**Prediction error** (Kouider et al., 2013; Stefanics et al., 2014)

Importantly, early neural responses reflect **regulatory integration** rather than predictive inference. Mismatch-related responses (often discussed in relation to MMN) become reliably observable only once regulatory integration attains sufficient temporal stability, consistent with the regulatory-threshold account.

C.4 Scale-Invariant Biological Imperative

C.4.1 Regulatory Stability as the Absolute Objective Function

Across all biological scales, regulatory activity is not arbitrary. It is constrained by a single, non-negotiable objective function: the active maintenance of non-equilibrium stability (Callen, 1985; Haken, 1990; Onsager, 1931; Prigogine, 1980). Living systems persist by continuously maintaining internal states within viable bounds while minimizing perturbations that would collapse this non-equilibrium organization.

This objective function can be decomposed into two inseparable components. Stabilization of internal state variables across time and minimization of perturbations that threaten systemic integrity. Importantly, neither component presupposes prediction, representation, or agency. Together, they define the minimal operational goal of life itself, independent of cognitive complexity or phenomenological capacity.

Within this framework, regulation is the primary means by which this objective function is satisfied. Regulatory processes operate through immediate, state-dependent coupling between internal variables and environmental constraints, without anticipatory computation. Prediction emerges only when accumulated regulatory stability allows the system to anticipate future perturbations at acceptable energetic and computational cost. Thus, prediction should not be understood as an intrinsic goal of biological systems, but as a secondary, high-cost strategy for extending regulatory control under increasing environmental complexity.

C.4.2 Scale-Invariant Continuity from Cells to Conscious Agency

The transition from cellular regulation to predictive cognition and ultimately to conscious agency does not require the introduction of new organizing principles or scale-specific transition terms. Across levels of biological organization, the same fundamental principle remains invariant: maintenance of internal stability through regulation.

What changes across development and evolution is not the principle itself, but the form of its implementation. At the cellular level, regulation is realized through membrane dynamics, ionic fluxes, and metabolic coupling. In embryonic and early neural systems, regulation operates through local feedback loops and distributed excitability (Fair et al., 2009; Kouider et al., 2013). In conscious agents, regulation is extended through environment-mediated causal interaction (Rochat, 2003) and, eventually, anticipatory modeling.

Within this framework, the absence of prediction in early biological systems and early development does not indicate limitation or deficit. Instead, it reflects a system that is functionally complete within its current regulatory regime, prior to the synthesis of the structural and energetic conditions required for prediction and conscious agency (Rochat, 2003). Prediction and agency emerge not as replacements for regulation, but as elaborations made possible by its prior stabilization (Rochat, 2003; Thompson, 2007; Varela et al., 1993).

D. Developmental Instantiation of the Proto-Conscious Stage: Neurodevelopmental Constraints, Phylogenetic Conservation, and Topological Invariance

D.1 Pre-phenomenal Characterization of Early Sensory and Autonomic Regulation

This section provides a physiological and neurodevelopmental characterization of sensory–motor and autonomic processes observed during the fetal period and early infancy, corresponding to the Proto-Conscious Stage defined in the main text. The phenomena described here are not treated as indicators of subjective experience or self-attribution, but rather as pre-phenomenal regulatory mechanisms operating under developmental constraints prior to the formation of stable causal structures supporting self–other differentiation.

During *early gestation (approximately 7–8 weeks)*, spontaneous fetal movements are observed that are mediated primarily by spinal reflex circuits (Prechtl, 1997; Winnubst et al., 2015). These movements are automatic and stereotyped, reflecting the initial functional activation of basic sensorimotor pathways rather than intentional action or experiential processing. At later stages *(around 12–14 weeks)*, reflexive behaviors such as sucking emerge (Lagercrantz & Changeux, 2009; Prechtl, 1997). These behaviors are mediated predominantly at the brainstem level and involve repeated coupling between localized sensory input (e.g., oral tactile stimulation) and motor output. Such coupling reflects the operation of recurrent sensorimotor loops, without implying cortical-level body representation or reflective processing.

By *approximately 25–27 weeks of gestation,* maturation of the auditory apparatus allows fetal exposure to low-frequency acoustic stimuli, including maternal cardiac and vocal signals. Auditory input at this stage is processed primarily through subcortical pathways involving the brainstem and thalamus (Graven & Browne, 2008; Kostović & Jovanov-Milošević, 2006). Rhythmic and temporally regular stimuli are associated with modulation of global arousal and autonomic state, whereas irregular or novel stimuli may transiently increase physiological activation (DeCasper & Fifer, 1980). These response patterns indicate that external sensory input begins to function as a state-modulating factor, rather than as a source of object-level representation or causal attribution.

Importantly, the physiological responses observed during this period do not require the assumption of subjective experience (Kouider et al., 2013). Instead, early affective and behavioral expressions are more parsimoniously described as manifestations of developing regulatory systems (Johnson, 2001; Kouider et al., 2013; Passos-Ferreira, 2024) that mediate transitions between relative physiological stability and perturbation. In both fetal and early postnatal stages, such regulation is dominated by brainstem and limbic circuits, with relatively limited engagement of cortically mediated integrative networks at this stage associated with explicit representation, inference, or self-related attribution (Johnson, 2001).

Developmental studies further indicate that individual differences in fetal motor activity and neonatal reactivity are not random. Baseline levels of activity and arousal show partial continuity (Hofer, 1994; Sroufe, 2002) from the prenatal period into early infancy, where they are expressed as differences in reactivity, activity level, and emerging self-regulatory capacity (Hofer, 1994). These continuities are commonly interpreted in terms of early-emerging biological temperament, shaped by genetic factors and progressively modulated by postnatal environmental and social conditions.

Crucially, such continuity does not imply the presence of subjective experience or an early form of selfhood in the fetus. Rather, it supports the view that temperamental biases are instantiated through developing neural and autonomic regulatory systems, prior to the availability of representational or causal architectures required for self–other differentiation.

Taken together, sensory–motor activity and physiological regulation observed during the fetal period and early infancy should be situated at a pre-phenomenal level of organization. These processes do not constitute precursors of conscious self-experience in a direct sense, but instead provide the regulatory substrate upon which later forms of environment-mediated causal interaction and state-dependent self-attribution can eventually emerge. This supplementary section thus clarifies how the biological observations summarized here align with, and support, the theoretical framework advanced in the main text.

D.2 Phylogenetic Conservation of Causal-Developmental Ordering

Despite vast differences in neuroanatomy and sensory dominance (e.g., vision in humans vs. olfaction in rodents), the functional sequence of causal organization within the Proto-Conscious Stage appears to be phylogenetically conserved. This suggests that the transition from closed physiological regulation to the threshold of conscious agency follows a widely observed topological roadmap. This roadmap consists of five sequential phases defined by changes in causal topology rather than specific behavioral markers. The species described in the Other Taxa entry in this section are illustrative examples.

D.2.1 Somatic Grounding (Internal Closed Loop)

- **Human:** Prenatal integration of tactile and proprioceptive signals (e.g., hand-to-face contact).
- **Other Taxa:** Occurs prenatally in precocial mammals (e.g., ungulates) or immediately post-hatching in birds/fish.
- **Commonality:** Establishment of the "body schema" as the internal reference coordinate. The system is closed to environmental causality (Damasio, 2010; Gallistel, 2013; Legrand, 2006; Prechtl, 1997).

D.2.2 Differential Arousal (Environment as State-Tuner)

- **Human:** Modulated primarily by auditory and vestibular inputs (maternal voice/movement).
- **Other Taxa:** Rodents rely on olfactory/tactile cues. Fish utilize lateral line hydrodynamic pressure.
- **Commonality:** External stimuli modulate internal physiological states (arousal/calmness) but are not yet processed as distinct causal objects (DeCasper & Fifer, 1980; Hepper, 1991; Moon et al., 2013; Moriceau & Sullivan, 2006).

D.2.3 Regulatory Stabilization (Statistical Safety)

- **Human:** Stabilization to familiar maternal cues, distress to novelty.
- **Other Taxa:** Widely observed habituation/sensitization mechanisms. Precocial birds imprint on the first moving object as a "regulatory base."
- **Commonality:** The environment acts as a statistical regulator. Familiar inputs reduce metabolic cost (stabilization), while deviant inputs trigger arousal (Ainsworth et al., 2014; Bowlby, 1999; Horn, 2004; Sroufe, 2002).

D.2.4 Sensory Field Expansion (Spatial Arena)

- **Human:** Delayed visual dominance (postnatal months 2–5).
- **Other Taxa:** Rapid onset in precocial species (e.g., chicks peck accurately within hours). Rodents map space via whisking.
- **Commonality:** The environment expands from a "state-tuner" to a "structured spatial arena." The organism begins to map external coordinates relative to the somatic ground (Gibson, 2015; Granrud, 1986; Mitchinson et al., 2011).

D.2.5 Proto-Interactive Organization (Threshold of Agency)

- **Human:** 6–9 months (emergence of means–end behavior).
- **Other Taxa:** Corvids (crows/magpies) show rapid onset of causal tool use. Primates follow a similar but accelerated trajectory compared to humans.
- **Commonality:** Accumulation of causal preconditions (e.g., object permanence, action-outcome linking). While timing varies (Heterochrony), this stage, widely observed, precedes the emergence of full Environment-Mediated Causal Interaction (e.g., complex social manipulation or MSR) (Emery & Clayton, 2004; Hofer, 1994; Rochat, 2003; Willatts, 1999).

D.3 Topological Invariance Under Sensory-Ecological Heterochrony and Natural Perturbation

Across sentient species, sensory ecologies systematically differ: habitat, niche, locomotion, and circadian constraints shape the relative input statistics available to each modality (e.g., tactile, auditory, visual). These modality-weighted input environments are therefore expected to generate heterochrony in the tempo and tuning of modality-linked regulatory subsystems. Importantly, such variation concerns rate, calibration, and route rather than the ordering of causal transitions. The ordering remains constrained by prerequisite causal topology (Lickliter, 2011; Turkewitz & Kenny, 1982), whereas ecological differences primarily determine how rapidly and robustly later refinements are instantiated and which modality-weighted pathways predominate.

Here, “stress test” is used in a methodological sense. A naturalistic perturbation that reweights input statistics, not an intervention that can revise prerequisite causal dependencies. The COVID-19 pandemic constitutes a large-scale perturbation of early-life input ecology, sharply reweighting social and sensorimotor exposure (Deoni et al., 2021) and early motor affordances (Backman et al., 2025) without rewriting the underlying causal architecture (Shonkoff et al., 2012). Accordingly, pandemic-associated developmental shifts are most parsimoniously interpreted as heterochronic modulation of functional development (tempo and tuning), often yielding asymmetric profiles (Backman et al., 2025) in which some domains show relative delay while others remain preserved or comparatively advanced (Deoni et al., 2021). Mechanistic details underlying activity dependence and modality-specific robustness to input-statistics perturbations are provided in Supplementary Material E.

E. Modality-Specific Robustness and Activity-Dependent Instantiation

E.1 Audition as an Early Exteroceptive Reference Signal (Why audition is baseline)

Across sensory modalities, audition exhibits a distinctive combination of properties that differentiate it from other early-developing systems. Unlike tactile, proprioceptive, or interoceptive signals (which primarily convey information about internal bodily state or require direct contact) auditory input reliably conveys changes occurring outside the body, often before physical interaction becomes unavoidable (DeCasper & Fifer, 1980; Hepper, 1991). Importantly, auditory signals reach early central processing stages with relatively short latencies and without requiring direct contact or visual exposure (Graven & Browne, 2008; Johnson, 2001) allowing them to modulate global arousal and autonomic state while preserving bodily integrity (DeCasper & Fifer, 1980; Hepper, 1991).

Under the present framework, the significance of audition in early development is not that it enables causal attribution or self–other boundary formation. Rather, it provides an early availability floor for exteroceptive state-tuning: a distal, non-contact channel that can remain informative even when locomotion is limited, object manipulation is immature, or visual access is intermittently constrained. In fetal and early infant development, such properties make audition particularly suited to act as a reference stream for differentiating internally generated fluctuations from externally driven perturbations at the level of arousal and autonomic regulation (Hepper, 1991). This functional role is compatible with the pre-phenomenal characterization of the proto-conscious stage. Auditory processing contributes to early state regulation and environmental sensitivity without constituting environment-mediated causal interaction as defined in the main text.

Crucially, the early developmental value of audition can be further motivated by energy-relevant constraints. “Implementation cost” in this context is not limited to long-range wiring cost, but includes (i) formation and maintenance of the peripheral apparatus, (ii) central pathway wiring and integrative infrastructure, and (iii) ongoing operational signaling demands required for reliable transduction and control (Attwell & Laughlin, 2001; Laughlin & Sejnowski, 2003). Across modalities, vision typically imposes exceptionally high energetic requirements across all three components (peripheral maintenance, long-range integration, and high-bandwidth processing), whereas interoception and many somatic channels can operate with lower-bandwidth, more locally closed loops. Audition occupies an intermediate-but-critical regime. The peripheral apparatus is mechanically vulnerable and physiologically demanding (e.g., ionic homeostasis supporting cochlear transduction). Yet its distal, non-contact access yields high regulatory return (Laughlin & Sejnowski, 2003) under tight metabolic budgets, as it can tune global state without requiring contact-driven interaction or mature visuomotor scaffolding (Table S4). Notably, high mechanical vulnerability does not imply late developmental priority. Rather, it increases the payoff of early functional stabilization, because failures in distal exteroceptive channels can be disproportionately costly for state regulation. This supports treating audition—along with somatosensation—as a robust baseline modality for the proto-conscious stage under statistically typical ecologies, even when other exteroceptive channels (e.g., vision) are intermittently constrained (Lickliter, 2011; Turkewitz & Kenny, 1982) (Table S2).

E.2 Activity-Dependent Instantiation in AP-Based Systems (Why input statistics matter)

A second constraint shaping early phase ordering concerns the distinction between structural formation and functional instantiation. In non-excitable systems void of action potential (AP), baseline maturation and growth are largely governed by genetically canalized programs and systemic trophic cues, showing limited dependence on everyday usage statistics. By contrast, in excitable, AP-based systems (such as neural and sensorimotor control loops, muscular systems, and rhythmic pacemaking circuits) gross structural formation follows developmental programs, but functional instantiation depends on patterned activity: synaptic refinement, microtuning of circuit dynamics, and performance stabilization scale with the frequency and statistical structure of inputs (Katz & Shatz, 1996; Winnubst et al., 2015). This activity dependence provides a mechanistic basis for why ecological perturbations (including pandemic-era reweighting of early social and sensorimotor input statistics) (Backman et al., 2025; Deoni et al., 2021) are expected to modulate developmental tempo and tuning, producing asymmetric profiles without implying any change in causal ordering (see Supplementary Material D3). Put differently, early phase transitions are constrained by what is structurally implementable, but later stabilization is constrained by what becomes functionally instantiable under the available input statistics.

In this context, modality differences matter because they differentially determine both the reliability of early input floors and the energetic costs of maintaining usable control-relevant signals. Somatosensation and audition provide comparatively robust early input: tactile signals are guaranteed under caregiving contact and self-generated movement, while auditory signals can remain available as distal state-tuners even when contact opportunities and visual exposure are limited. By contrast, vision despite its high eventual centrality for spatial organization tends to require substantial postnatal activity-dependent refinement and carries higher formation/maintenance and integration costs, making it less suitable as an early baseline channel for stabilizing global state under restricted ecologies (Johnson, 2001; Lickliter, 2011; Turkewitz & Kenny, 1982) (Table S4). These constraints jointly motivate the emphasis placed here on audition and somatosensation as early baselines for proto-conscious stage characterization (Table S3).

Table S3. **Sensory Modality Constraints Shaping Early Instantiation: Distal Access, Latency, and Activity Dependence**

Sensory Modality	Primary Receptor Location	Mode of Signal Transmission	Approx. Early Processing Latency	Effective Operating Distance	Mechanical Vulnerability	Activity-Dependent Instantiation (AP-based)	Predominant Role in Early Development
Tactile (Touch)	Body surface (skin)	Direct mechanical contact	~20–30 ms Developmentally variable (Johnson, 2001; Prechtl, 1997)	Contact-only	Low	**High** (Early spontaneous / evoked activity)	Regulation of bodily contact & **Somatic Grounding**
Proprioceptive	Muscles, joints, tendons	Internal stretch & position signals	~20 ms (Johnson, 2001; Prechtl, 1997)	Internal (0 distance)	Low	**Moderate** (Self-generated movement)	Postural control & movement coordination
Interoceptive	Visceral organs, vasculature	Internal chemical & mechanical signals	Slow / diffuse context-dependent (Feldman et al., 2024; Seth, 2013)	Internal (0 distance)	Low	**Low** (Primarily non-excitable modulation)	Homeostatic state regulation
Olfactory	Nasal epithelium	Airborne chemical diffusion	Moderate context-dependent (Graven & Browne, 2008; Kostović & Jovanov-Milošević, 2006)	Proximal-to-distal (diffusion; context dependent)	Moderate	**Moderate** (Environmental exposure)	Detection of proximal environmental cues

Sensory Modality	Primary Receptor Location	Mode of Signal Transmission	Approx. Early Processing Latency	Effective Operating Distance	Mechanical Vulnerability	Activity-Dependent Instantiation (AP-based)	Predominant Role in Early Development
Visual	Retina	Photonic stimulation	~40–60 ms (Johnson, 2001; Turkewitz & Kenny, 1982)	Distal (line-of-sight)	High	**High** (Postnatal activity-dependent pruning)	Spatial structure & object differentiation
Auditory	Inner ear (cochlea)	Mechanical vibration via air or tissue	~10–20 ms Developmentally variable (Hepper, 1991; Johnson, 2001)	Distal (non-contact; occlusion-tolerant)	Very high	**High** (Activity-driven refinement)	Early detection of distal environmental changes (Hepper, 1991)

Note:

- Latency values reflect approximate early sensory processing stages (e.g., ERP onset ranges), not higher-order perceptual integration.
- **Vulnerability** refers to susceptibility to mechanical/functional disruption. Audition is highly vulnerable but paradoxically robust as a baseline because it requires no direct physical contact for instantiation.
- **Activity-Dependent Instantiation** refers to the degree to which functional maturation requires action potential (AP) signaling and activity-driven synaptic refinement.
- Functional roles describe predominant contributions in prenatal and early postnatal stages, not mature perceptual functions.
- **Latency Context**: For Tactile and Auditory modalities, "Developmentally variable" refers to latency shifts due to ongoing myelination and synaptogenesis (i.e., structural maturity).

Table S4. **Energy-relevant constraints across sensory modalities (qualitative heuristic)**

Sensory Modality	Peripheral apparatus (formation & maintenance)	Central pathways (wiring & integration)	Operational signaling (transduction & control)	Representative energy-relevant mechanisms (illustrative)
Vision	High	High	High	phototransduction + retinal maintenance; high-bandwidth scene processing; extensive long-range integration and wiring costs (Attwell & Laughlin, 2001; Bullmore & Sporns, 2012)
Audition	Moderate–High	High	High	cochlear ionic homeostasis/endocochlear potential; fast temporal precision pathways (Laughlin & Sejnowski, 2003); continuous temporal tracking
Tactile, Proprioceptive	Moderate (distributed)	Moderate	Low–Moderate (event-driven; self-motion dependent)	distributed mechanoreceptors + short-range spinal/brainstem loops; proprioceptive feedback during movement; comparatively lower distal bandwidth
Olfaction	Low–Moderate	Low–Moderate (species-dependent)	Moderate (context-dependent)	receptor turnover; diffusion-limited input statistics; niche-dependent reliance (e.g., higher in rodents)
Interoception	Low	Low	Low–Moderate (tonic regulation)	visceral afferents + endocrine/chemical milieu; homeostatic control loops (Haueis & Colaço, 2025; Sterling, 2012); low-bandwidth but persistent signaling

Note:

- Values indicate where constraints concentrate, not cross-modality ATP totals.
- Profiles vary by taxon, developmental stage, and anatomical scope (periphery vs central pathways).
- The table motivates baseline-channel arguments (availability floor, distal access, activity dependence), not a “ranking” of senses.
- The metabolic and latency profiles are grounded in the 'economy of brain network organization' (Bullmore & Sporns, 2012) and the thermodynamic costs of signaling in the grey matter (Attwell & Laughlin, 2001). Specifically, the hierarchical priority of audition and somatosensation as baseline modalities is motivated by their high 'regulatory return' relative to the extreme metabolic investment required for high-bandwidth visual integration (Lickliter, 2011; Turkewitz & Kenny, 1982).

F. Cross-species Comparative Analysis of the Hierarchical Components of MSR

This supplementary section provides a concise cross-species comparison of the neurocognitive components commonly implicated in mirror self-recognition (MSR). Its purpose is not to redefine MSR or to argue for its centrality in consciousness research, but to support the exclusion of MSR from UBCAT's functional definition of consciousness by showing that MSR reflects the convergence of multiple higher-order capacities rather than a core prerequisite for phenomenal experience. In other words, MSR is treated here as an optional, late-emerging composite outcome whose success conditions are stricter than the minimal causal agency criteria used in UBCAT.

F.1 MSR as a hierarchical composite outcome

Across taxa, MSR performance does not map onto a single cognitive function or a single neural substrate. Instead, consistent MSR outcomes appear only when multiple components are sufficiently integrated, including (i) multisensory integration for matching visual input to proprioceptive/tactile contingencies (Anderson, 1984; Blanke & Metzinger, 2009), (ii) causal inference linking self-generated action to observed outcomes, (iii) a stable body schema supporting self-model alignment, and (iv) executive control enabling sustained hypothesis testing and error correction under conflicting cues (Rochat, 2003). This dependency profile implies that MSR is a stringent benchmark for conceptual self-attribution under a specular mapping (Suddendorf & Butler, 2013; Zahavi, 2005), not a minimal benchmark for conscious experience.

Crucially, this pattern indicates that MSR success reflects the late-stage convergence of distributed neurocognitive capacities, rather than the presence or absence of conscious experience per se. Conversely, MSR failure does not imply the absence of affective processing, perception, or phenomenally relevant states, but rather the absence of a particular configuration of higher-order integrative functions.

Accordingly, MSR is best understood as an external behavioral marker of conceptual self-attribution, not as a necessary condition for consciousness (Rochat, 2003). This comparative perspective supports the UBCAT framework's decision to exclude MSR from the functional definition of consciousness, while retaining it as a valuable (but non-fundamental) index of advanced self-referential cognition.

F.2 Ecological scarcity of reflective media and the limits of "training" interpretations

It is noteworthy that in natural environments, materials capable of producing stable, specular reflections analogous to mirrors are extremely rare. Apart from transient water surfaces or crystalline structures, most organisms are unlikely to encounter consistent reflective media during development.

This ecological constraint raises a theoretical question regarding mirror self-recognition (MSR): whether failures in MSR performance across species necessarily reflect the absence of self-related representations, or instead reflect the absence of repeated exposure to the physical regularities required to interpret mirror-like reflections.

However, within the framework proposed here, this possibility does not undermine the hierarchical interpretation of MSR. Even under conditions of repeated exposure or training, successful MSR would still require the prior availability of multiple neurocognitive prerequisites, including stable body representations, visuomotor integration (Rochat, 2003; Willatts, 1999), causal inference, and executive control. In the absence of these components, increased exposure alone would not be sufficient to induce genuine self-recognition.

Recent work further reinforces the interpretation of MSR as a composite outcome rather than a core prerequisite for consciousness. Notably, rhesus macaques (historically classified as failing standard MSR) have been reported to exhibit self-directed mirror behaviors following intensive visuomotor/visuosomatosensory association training (Chang et al., 2015, 2017) in which mirror information is contingently paired with stimulation on the animal's own face. These results suggest that MSR-like performance can, in some cases, be induced by learning stable cross-modal contingencies (e.g., between a visual "mark" seen in the mirror and somatic consequences on one's own body), without implying the spontaneous emergence of human-like conceptual self-attribution. The broader implication is not that MSR is "mere conditioning," but that MSR performance is sensitive to the availability and calibration of multiple prerequisite components (multisensory integration, contingency learning, body representations, and executive control), consistent with the hierarchical-convergence view adopted here (De Veer & van den Bos, 1999).

In humans, the same logic motivates a cautious developmental interpretation: infants' mirror-related competencies unfold within repeated caregiver-mediated interaction routines (e.g., joint attention episodes around reflective surfaces, socially scaffolded contingency mapping, and culturally patterned mirror use). Accordingly, MSR should be treated as a socially embedded developmental achievement that depends on opportunities for structured exposure and calibration, but as a context-free readout of phenomenal experience.

From this perspective, ecological scarcity of reflective media may constrain opportunities for MSR learning, but does not relax the hierarchical constraints that define MSR as a late-emerging, composite outcome rather than a trainable perceptual skill.

Table S5. **Cross-species Comparison of Hierarchical Components Required for MSR**

Species	Sensory Integration	Causal Inference	Body Schema	Executive Control (PFC-like)	MSR Outcome
Chimpanzee	✓	✓	✓	✓	Pass (Gallup, 1970)
Orangutan	✓	✓	✓	✓	Pass (Suarez & Gallup, 1981)
Asian elephant	✓	Partial	✓	Partial	Partial (Shumaker et al., 2011)
Eurasian magpie	✓	✓	Partial	Partial	Pass (Prior et al., 2008)
Rhesus macaque	✓	Partial	✓	Partial	Fail (Chang et al., 2015; De Veer & van den Bos, 1999)
Dog	✓	Limited	✓	Limited	Fail

Note: "Pass" indicates consistent evidence of MSR under standard mark tests. "Partial" indicates context-dependent or inconsistent performance. The table is used for *dependency illustration* rather than for ranking species.

Interpretive summary

Successful MSR is observed only when multiple hierarchical components are sufficiently integrated (Rochat, 2003). Species with sophisticated social behavior or affect-like responsiveness (e.g., dogs) can fail MSR tasks, while phylogenetically distant species (e.g., corvids) can pass under specific conditions (Emery & Clayton, 2004; Nieder, 2017; Prior et al., 2008). This dissociation supports treating MSR as a high-threshold behavioral index of conceptual self-attribution (Rochat, 2009; Zahavi, 2005) rather than a minimal criterion for UBCAT-defined consciousness.

G. Boundary Conditions of UBCAT: Non-biological Systems (LLMs and Robotics)

This section lists mechanistic boundary conditions under which UBCAT's biological loop-closure criterion does not apply to current artificial systems, independent of behavioral fluency.

G.1 Mechanistic Non-equivalence Between Biological and Artificial Systems

While contemporary LLMs and robots may exhibit behaviors that resemble aspects of biological cognition, their generative and control mechanisms are implemented in architectures that do not instantiate the key biological substrates presupposed by UBCAT (Man & Damasio, 2019; Seth, 2025). Core prerequisites include, but are not limited to:

- **Membrane-based signal transduction**
  No neuron-like depolarization–repolarization dynamics operating as the basis of recurrent excitability and state-dependent integration.
- **Neurochemical modulation and global state coupling**
  No organism-scale neuromodulatory milieu that binds physiological condition to control policy through chemically mediated regulation.
- **Biological Sensory transduction**
  No receptor-based transformation of physical energy into organism-relative sensory signals with developmental tuning under embodied constraints.
- **Interoceptive variables and homeostatic targets**
  No intrinsic internal norms whose deviation is obligatorily regulated to maintain viability (i.e., no homeostasis as an objective function) (Man & Damasio, 2019; Sterling, 2012).
- **Closed, state-dependent self-attribution within a living control loop**
  No biologically instantiated self-referential causal variable that is constituted as bodily state and that modulates action selection under viability constraints.

As a result, the recurrent sensory–interoceptive integration loops central to UBCAT-defined conscious agency are non-existent in current LLMs and typical robotic architectures, regardless of surface-level functional similarity.

G.2 Apparent Self-Reference and the Mirror Test in Artificial Systems

Robotic systems and AI-driven vision models can be engineered to display behaviors that resemble mirror self-recognition or body-awareness. However, under UBCAT, such behaviors do not constitute self-referential causal control.

In robotic systems, apparent "self-recognition" arises from coordinate transformation, sensor fusion, and physical modeling. Sensor inputs are mapped onto joint coordinates and motor outputs through predefined control architectures. While this enables precise movement and adaptive control, it does not involve the attribution of action to an internally experienced bodily state (Haggard, 2017; Seth & Tsakiris, 2018).

- **Coordinate-based control** (artificial systems): transformation and execution without self-attribution.

- **Self-referential bodily control** (biological systems): action selection modulated by internally attributed bodily states.

Mirror-test–like behaviors in robots or AI systems therefore reflect surface-level functional mimicry rather than the emergence of conscious self-reference.

G.3 Functional Isomorphism Without Mechanistic Equivalence

UBCAT does not deny the functional sophistication of artificial systems. LLMs may display contextual sensitivity, coherence across time, and flexible output generation. Robotic systems may engage in complex environment-directed behavior.

However, under UBCAT, functional similarity does not adjudicate consciousness. Conscious agency requires that internal states operate as self-attributed causal variables within a biologically instantiated, closed control loop. Where the requisite biological substrates are not instantiated, the system remains outside UBCAT’s scope (Albantakis et al., 2023; Butlin et al., 2023).

Thus, similarities between artificial and biological systems should be interpreted as cases of functional isomorphism without mechanistic equivalence.

Table S6. **Comparison between biological nervous systems and non-biological artificial systems (LLMs and robotics) across core mechanistic dimensions relevant to the UBCAT framework.**

Dimension	Biological Nervous System	LLM / Robotics
Signal basis	Membrane depolarization	Electrical state transitions
Sensory input	Receptor-based transduction	Pre-encoded sensor data
Interoception	Present	Absent
Homeostasis	Required	Not applicable
Self-attribution	State-dependent	Not instantiated
Consciousness (UBCAT)	Possible	Not satisfied

Note: The table highlights differences in signal basis, sensory transduction, interoceptive regulation, and self-attribution, clarifying why non-biological systems fail to satisfy the minimal mechanistic conditions for consciousness under UBCAT.

G.4 Implications for AI Consciousness Debates

By specifying these boundary conditions, UBCAT provides a principled framework for evaluating claims about artificial consciousness. Rather than relying on behavioral criteria alone, UBCAT grounds the debate in mechanistic and causal architecture.

Under this framework, current LLMs and robotic systems do not qualify as conscious agents. This is not because they are insufficiently complex, but because they lack the biological causal substrates upon which conscious agency, as defined by UBCAT, depends (Birch, 2024; Seth, 2025).

Accordingly, UBCAT does not classify non-biological systems as conscious agents. The term consciousness-like is used here as a classificatory convenience, not as an ontological claim about subjective experience. However, to avoid conflating mechanistic exclusion with functional triviality, this section proposes that such systems be described as **consciousness-like systems** rather than as conscious systems. This designation acknowledges that artificial systems may exhibit behavioral, informational, or functional patterns that resemble certain outward aspects of conscious processing, while remaining mechanistically distinct from biologically instantiated conscious agency.

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