

# The Gravity of Empowerment: Synthesizing Neural Criticality, Gastric Spacetime, and Causal Model Construction in Human Development

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## Abstract

The developmental trajectory from early childhood to adulthood is characterized by profound cognitive and physiological transformations, historically studied in isolation across cognitive psychology and network biophysics. While cognitive models emphasize "empowerment gain"—the intrinsic motivation to construct accurate causal models by maximizing the mutual information between an agent's actions and environmental outcomes—the biophysical substrates required to thermodynamically support this massive computational scaling have remained elusive. This paper introduces a novel interdisciplinary framework synthesizing the principles of neural criticality with the analogue gravity dynamics of the gut-brain axis. We propose that the maturing human brain's progression toward self-organized criticality is fundamentally anchored by the concurrent maturation of the Enteric Nervous System. Within this model, the gastrointestinal tract functions as an effective spacetime metric and a vital thermodynamic sink, safely dissipating the immense metabolic costs associated with rapid causal learning. By framing gastric electrophysiology as a stabilizing topological boundary, we demonstrate that the organism's pursuit of cognitive empowerment is inextricably linked to the structural integrity of this unified neuro-visceral network. Furthermore, this synthesis provides a precise biophysical etiology for the developmental vulnerabilities of adolescence: the psychiatric distress and dysautonomia frequently observed during this period are reframed as supercritical instabilities arising from a temporary decoupling of the central cognitive manifold from its visceral gravitational anchor. Ultimately, this paradigm establishes that advanced causal reasoning and cognitive empowerment are not merely localized neural computations, but emergent properties of a perfectly calibrated, body-wide thermodynamic and topological system.

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# Introduction

The transition from early childhood through adolescence and into adulthood represents one of the most profound and dynamic periods of physiological and cognitive transformation in the human lifespan. Historically, the study of this developmental epoch has been partitioned into disparate scientific domains. Developmental cognitive scientists and psychologists have meticulously mapped the emergence of causal reasoning, observing how children act as intuitive scientists who actively intervene in their environments to construct accurate models of the world.<sup>1</sup> Concurrently, biological physicists, network neuroscientists, and gastroenterologists have tracked the physical maturation of the central and autonomic nervous systems, framing human development as a progression toward precise homeostatic set-points.<sup>1</sup>

Recent theoretical breakthroughs in both artificial intelligence and biophysics provide a unique opportunity to unify these isolated perspectives. In the realm of cognitive science and machine learning, researchers have identified "empowerment gain"—the maximization of mutual information between an agent's actions and their outcomes—as the fundamental intrinsic motivation driving causal model construction.<sup>1</sup> Simultaneously, advanced network electrophysiology demonstrates that the maturing human brain systematically shifts toward a state of "self-organized criticality," an optimal computational boundary between order and chaos.<sup>1</sup> Crucially, this optimal neural state regulates the peripheral autonomic system—specifically the gastrointestinal tract, which can be mathematically modeled as an analogue gravity system where the physical medium of the stomach acts as a biological spacetime metric.<sup>1</sup>

This comprehensive report presents an exhaustive synthesis of these advanced frameworks. By systematically integrating the behavioral psychology of empowerment gain with the physical mechanics of neural criticality and gastric analogue gravity, a unified theory of human neuro-visceral maturation is established. The central thesis posits that the cognitive drive for empowerment is the behavioral manifestation of a neural network achieving a critical phase transition. Furthermore, the successful construction of causal models by a critical brain produces a high-fidelity vagal tuning signal that smooths the biological spacetime of the viscera, optimizing physiological flow. Conversely, developmental failures in causal empowerment maintain the brain in a chaotic, supercritical state, leading to localized collapses in visceral spacetime—analogue event horizons—that transmit catastrophic distress signals and drive profound psychiatric pathology.<sup>1</sup>

## The Computational Architecture of Causal Learning and Empowerment

Learning the causal structure of the environment is arguably the most fundamental and complex computational problem faced by human cognition.<sup>1</sup> Unlike associative learning, which merely detects statistical correlations between passively observed variables, causal learning

requires an understanding of the underlying mechanisms that govern how variables interact.<sup>1</sup> This distinction is critical for survival and adaptation, as only an accurate causal model of the world permits successful, goal-directed interventions.<sup>1</sup>

## The Interventionist Account and the Bayes Net Formalism

Over the past quarter-century, cognitive scientists have relied heavily upon the Causal Bayes Net formalism to model how humans acquire causal knowledge.<sup>1</sup> In this framework, causal relationships are represented as directed acyclic graphs, where nodes represent variables and directed edges represent the causal mechanisms linking them. The Bayes net formalism assumes an "interventionist" account of causation.<sup>1</sup> Under this paradigm, a variable  $X$  is considered a cause of a variable  $Y$  if, and only if, an exogenous intervention that forces a change in the value of  $X$  reliably leads to a corresponding change in the value of  $Y$ .<sup>1</sup>

This interventionist perspective differentiates causal inference from mere prediction. While observing the correlation between a barometer dropping and the arrival of a storm allows one to predict the weather, intervening to physically lower the needle on the barometer will not cause a storm. Causal knowledge is distinctive because it enables the reverse engineering of the universe; given a pattern of interventions and the resulting associative data, an ideal Bayesian learner can infer the specific causal graph that generated the data.<sup>1</sup>

Empirically, preschool children demonstrate remarkable proficiency in utilizing Bayesian inference to deduce correct causal hypotheses from complex data patterns.<sup>1</sup> However, from a purely computational perspective, exact Bayesian causal inference is notoriously intractable. The space of possible causal hypotheses grows exponentially with the number of variables, creating a search problem that cannot be solved by brute force.<sup>1</sup> While some developmental theorists posit that innate "core knowledge" constraints this hypothesis space, this innate perspective undermines the primary evolutionary advantage of causal learning: the capacity to comprehend and master entirely novel, counterintuitive causal structures, such as modern technological artifacts or abstract scientific principles.<sup>1</sup>

## The Reinforcement Learning Bridge: Information-Theoretic Empowerment

To address the tractability problem and explain the active, exploratory nature of human learning, researchers have looked to the intersection of cognitive science and deep reinforcement learning (RL).<sup>1</sup> Traditional RL agents operate by maximizing an external utility function or reward signal.<sup>1</sup> However, classical RL struggles significantly in the high-dimensional, open-ended, and non-stationary environments characteristic of the real world, primarily due to the exploration-exploitation trade-off.<sup>1</sup>

To overcome these limitations, modern RL frameworks incorporate "intrinsic motivations"—internal epistemic rewards that guide behavior in the absence of external

validation.<sup>1</sup> While simple curiosity or novelty-seeking algorithms promote exploration, they often succumb to the "noisy TV" problem. In this scenario, an agent seeking pure information gain becomes transfixed by a source of random, uncontrollable stochasticity (like static on a television screen), paralyzing its ability to learn actionable models.<sup>1</sup>

The concept of "empowerment" resolves this fatal flaw. Originally formulated in the evolutionary computation literature to explain the emergence of intelligence following the Cambrian explosion, empowerment acts as a universal, agent-centric measure of control.<sup>1</sup> An agent seeking empowerment is intrinsically rewarded for maximizing the channel capacity, or mutual information, between its specific actions (actuators) and the resultant sensory outcomes (sensors).<sup>1</sup>

Mathematically, empowerment ( $\mathcal{E}$ ) over a specific time horizon is defined by the maximum mutual information between the sequence of actions ( $A$ ) and the future state ( $S$ ):

$$\mathcal{E} = \max_{p(a)} I(A; S) = \max_{p(a)} (H(S) - H(S|A))$$

where  $H(S)$  represents the Shannon entropy of the future state, and  $H(S|A)$  represents the conditional entropy of the future state given the agent's actions.<sup>3</sup>

This profound mathematical formulation breaks empowerment down into two synergistic motivational drives:

1. **Variability ( $H(S)$ ):** To maximize empowerment, the agent must maximize the total entropy or variety of the states it can reach. This pressure ensures that the agent actively explores the widest possible range of actions, preventing it from exploiting a single, repetitive interaction.<sup>1</sup>
2. **Controllability ( $-H(S|A)$ ):** Concurrently, the agent must minimize the conditional entropy of the outcome given its action. In other words, variation in the action must systematically and predictably dictate the variation in the outcome.<sup>1</sup>

By demanding both variability and controllability, empowerment seamlessly bridges Bayesian causal learning and reinforcement learning. If an agent learns an accurate causal model, it necessarily increases its empowerment because it understands which interventions yield predictable control. Vice versa, an agent intrinsically driven to maximize empowerment will naturally discard random noise (uncontrollable variability) and gravitate toward relationships that form the basis of accurate causal world models.<sup>1</sup>

## Empirical Signatures of Empowerment: The Star

# Machine Paradigms

While the theoretical link between empowerment and causal model construction is mathematically robust, establishing its psychological reality requires rigorous empirical validation. To determine whether human learners actually utilize empowerment gain to guide their causal interventions, a series of innovative experiments were conducted with children (ages 5 to 10) and adults, systematically isolating the distinct components of controllability and variability.<sup>1</sup>

## Study 1: Isolating Controllability and Variability

In the first major empirical paradigm, 80 children and 120 adults were immersed in a virtual environment and introduced to three distinct "Star Machines." Each machine featured multiple slots and generated different outputs based on the objects placed within them, requiring participants to infer the underlying causal structure through observation.<sup>1</sup>

The three machines were carefully designed to represent specific information-theoretic profiles:

1. **The Purely Controllable Machine:** This device generated a single, deterministic output (e.g., always producing a medium star) regardless of the specific slot used. It offered perfect predictability but zero dynamic range or variability.<sup>1</sup>
2. **The Purely Variable Machine:** This device functioned as a random stochastic generator. It produced a wide variety of outputs (small, medium, and large stars), but the outputs had no systematic relationship to the slot chosen. It offered high entropy but zero controllability.<sup>1</sup>
3. **The Controllable and Variable Machine:** This device embodied true empowerment. It produced a variety of distinct outputs, but each outcome perfectly correlated with the specific slot utilized (e.g., small slots produced small stars, large slots produced large stars). It offered maximum mutual information between the agent's choice and the outcome.<sup>1</sup>

Following an observational phase, participants were subjected to rigorous causal generalization tasks that demanded active intervention. The tasks scaled in complexity: extending the structure to a new output value (creating an "extra small" star), applying the structure to a new object entirely (manufacturing hats of specific sizes), and transferring the causal logic to a novel perceptual modality (producing light bulbs of specific brightness levels).<sup>1</sup>

The empirical results conclusively demonstrated that human learners utilize empowerment to design causal interventions. When tasked with generalizing to a new output value, 80.83% of adults and 46.25% of children correctly selected the newly appended slot on the Controllable and Variable machine, performing significantly above chance.<sup>1</sup> Furthermore, across all generalization tasks, both children and adults overwhelmingly avoided the Purely Variable machine, despite its capacity to generate the full range of required outcomes. Because the

random machine could not guarantee a desired outcome in a single intervention, its lack of controllability rendered it useless for reliable causal engineering.<sup>1</sup>

## **Study 2: Parsing Simultaneous Dimensions of Variance**

Real-world causal learning is rarely as neatly compartmentalized as the machines in Study 1. Objects possess myriad simultaneous features, some of which are causally relevant (empowering) and some of which are mere noise. Study 2 increased the complexity of the paradigm by presenting 66 children and 60 adults with machines that embedded two features of variation—size and hue—within a single device.<sup>1</sup>

In one machine, the hue of the output varied systematically and predictably based on the slot used, while the size fluctuated randomly. In the second machine, this mapping was reversed: size was controllable, but hue was stochastic.<sup>1</sup> Participants were required to recognize the reliable structure while actively ignoring the highly salient, yet uncontrollable, source of variability.<sup>1</sup>

The findings replicated and extended the conclusions of the first study. When asked to generate an "extra large" outcome, 63.33% of adults and 45.50% of children accurately intervened on the size-controllable machine. Conversely, when asked to produce an "extra bright" outcome, 70% of adults and 42.40% of children correctly selected the hue-controllable machine.<sup>1</sup> Explicit preference testing confirmed these results: 80% of adults and 72.73% of children chose the size machine to "make things bigger," demonstrating a highly sophisticated ability to selectively attend to the dimension that offered high mutual information between action and outcome.<sup>1</sup>

## **The Contextual Divergence: Work Versus Play**

Perhaps the most revealing insight from these behavioral studies is the explicit divergence in machine preference based on the contextual framing of the task. When participants were asked which machine they would keep for "work" (a goal-directed context requiring reliable outcome generation), both adults (75%) and children (48.75%) demonstrated a massive, statistically significant preference for the Controllable and Variable machine.<sup>1</sup>

However, when the constraint of utility was removed and participants were asked which machine they would keep to simply "play" with, a profound shift occurred. Adults maintained a strong preference for the empowering Controllable and Variable machine (59.17%), though their selection of the Purely Variable machine increased significantly.<sup>1</sup> Children, conversely, exhibited a complete dissolution of their preference for controllability. In the play context, children's choices shifted dramatically toward the Purely Variable machine, effectively abandoning empowerment in favor of pure information entropy.<sup>1</sup>

This behavioral divergence reveals a fundamental developmental mechanism. Children, functioning as early-stage causal learners, utilize undirected play to aggressively sample the environment. By embracing pure variability and tolerating high levels of unpredictability, they

maximize their exposure to novel states, mapping the boundaries of the hypothesis space. As the individual matures into adulthood, the cognitive architecture shifts away from raw exploration toward the strict exploitation of controllable variance.<sup>1</sup> Understanding the physical mechanics that drive this shift requires an examination of the brain's evolving network electrophysiology.

<b>Context / Cohort</b>	<b>Preferred Machine Profile</b>	<b>Dominant Information-Theoretic Drive</b>	<b>Behavioral Strategy</b>
<b>Adults (Work)</b>	Controllable & Variable	Empowerment (Maximized Mutual Info)	Goal-Directed Causal Intervention
<b>Children (Work)</b>	Controllable & Variable	Empowerment (Maximized Mutual Info)	Goal-Directed Causal Intervention
<b>Adults (Play)</b>	Controllable & Variable	Sustained Empowerment / Mild Entropy	Structured Exploration
<b>Children (Play)</b>	Purely Variable	Pure Entropy / Uncontrollable Variance	Unconstrained Environmental Sampling

Table 1: Distribution of behavioral preferences and information-theoretic drives across developmental cohorts and task contexts.<sup>1</sup>

## **The Neurocomputational Substrate: Trajectories of Neural Criticality**

The psychological transition from the high-variance, entropy-seeking play of childhood to the high-control, empowerment-driven work of adulthood is not a mere accumulation of

experience; it is physically mandated by profound structural and dynamic shifts in the human brain. To process complex causal models, the brain must balance two competing computational imperatives: the need to transmit signals rapidly across vast neural networks (integration) and the need to maintain localized, specialized processing without descending into chaotic seizures (segregation).<sup>1</sup>

## **The Phase Transition of the Maturing Mind**

In the realm of statistical physics and complex systems theory, networks that successfully balance these opposing forces are said to operate at a "critical phase transition." The critical point represents a marginal boundary separating two distinct operational regimes.<sup>1</sup> On one side lies the subcritical state, characterized by extreme inhibition dominance. In a subcritical network, neural signals decay rapidly, preventing information from traversing the brain; the system is highly ordered but computationally stagnant and unresponsive.<sup>1</sup>

On the opposite side lies the supercritical state, characterized by excitation dominance. In this regime, even minor sensory inputs trigger massive, runaway cascades of neural firing. The system is highly excitable but chaotic, generating immense endogenous noise that corrupts precise information processing and prevents reliable causal tracking.<sup>1</sup>

When a neural network is perfectly poised at the critical boundary between these two phases, it exhibits emergent properties that are mathematically optimal for advanced computation. A critical brain possesses maximized dynamic range, optimal information transmission capacity, scale-free network activity, and profound susceptibility.<sup>1</sup> Susceptibility refers to the network's unparalleled capacity to reorganize and react to subtle, complex inputs without destabilizing—an absolute requisite for computing the mutual information necessary for empowerment gain.<sup>1</sup>

## **The Ontogeny of the Excitation-Inhibition Balance**

The human brain does not natively inhabit this optimal critical state during its early development. Extensive longitudinal resting-state electroencephalography (EEG) studies tracking healthy individuals from age 10 through 33 reveal that the brain systematically migrates toward criticality across the developmental transition from adolescence to adulthood.<sup>1</sup>

This migration is quantified through highly specific statistical markers of complexity. As individuals mature, their neural networks exhibit profound, spectrally-widespread increases in Long-Range Temporal Correlations (LRTC). LRTCs are calculated using Detrended Fluctuation Analysis (DFA), where a DFA exponent approaching 1.0 indicates a system operating near the critical boundary.<sup>1</sup> Concurrently, the adult brain demonstrates increased amplitude bistability (BiS)—the capacity of a neural population to spontaneously vacillate between high- and low-amplitude states without altering external control parameters, confirming the presence of a highly flexible, critical network.<sup>1</sup>

The biological mechanism driving this migration is the aggressive recalibration of the synaptic excitation-to-inhibition (E/I) balance.<sup>1</sup> Throughout adolescence, the cortex undergoes a massive structural remodeling. Redundant excitatory glutamatergic synapses are aggressively pruned, while inhibitory signaling is heavily potentiated.<sup>1</sup> This potentiation is primarily mediated by the maturation of fast-spiking, parvalbumin-positive (PV+) GABAergic interneurons, particularly within the higher-order association cortices such as the prefrontal cortex (PFC).<sup>1</sup> As the individual approaches adulthood, these mature PV+ interneurons are physically encapsulated and stabilized by specialized extracellular matrix structures known as perineuronal nets (PNNs), which close the windows of developmental hyper-plasticity and cement the mature, critical E/I set-point.<sup>1</sup>

Oscillatory Band	Frequency Range (Hz)	Age-Related E/I Shift	Shift in Criticality Markers (DFA & BiS)	Developmental Trajectory
Theta ( $\theta$ )	4.0 - 8.3	Decrease	Increase	Supercritical → Near-Critical
Alpha ( $\alpha$ )	8.3 - 13.4	Decrease	Increase	Supercritical → Near-Critical
Beta ( $\beta$ )	13.4 - 27.6	Decrease	Increase	Supercritical → Near-Critical
Gamma ( $\gamma$ )	27.6 - 57.6	Increase	Decrease	Subcritical → Cross-frequency coupled

Table 2: Frequency-specific developmental trajectories of the E/I balance and markers of neural criticality across the transition from adolescence to adulthood.<sup>1</sup>

As outlined in Table 2, this developmental maturation is highly complex and frequency-specific. The foundational, low-frequency systems of the brain—encompassing the theta ( $\theta$ , 4.0–8.3 Hz), alpha ( $\alpha$ , 8.3–13.4 Hz), and beta ( $\beta$ , 13.4–27.6 Hz) bands—experience a massive net decrease in their functional E/I ratio due to the surge in GABAergic inhibition.<sup>1</sup> During childhood and adolescence, these widespread networks operate in a slightly supercritical, excitation-dominant state, characterized by low DFA and high neural noise.<sup>1</sup> The maturation of inhibition reins in this runaway excitation, pulling these global coordinating networks down to the critical boundary, thereby stabilizing cognition.<sup>1</sup>

Conversely, the highly localized high-frequency gamma ( $\gamma$ , 27.6–57.6 Hz) networks, which govern acute sensory processing, experience a relative increase in their E/I ratio.<sup>1</sup> However, their emergent critical dynamics are simultaneously suppressed by the powerful, newly matured low-frequency oscillations via cross-frequency coupling. This top-down inhibitory control truncates the temporal persistence of high-frequency bursts, effectively eliminating endogenous noise and ensuring that sensory information is routed precisely to support accurate causal modeling.<sup>1</sup>

The physical validity of this transition is corroborated by computational simulations utilizing the CRITICAL Oscillations (CROS) model.<sup>1</sup> By simulating a highly coupled network of recurrent artificial neurons (75% excitatory, 25% inhibitory), researchers demonstrated that subtly altering the connection density between these units maps the entire developmental state space. When the artificial network perfectly balances excitation and inhibition, it spontaneously generates the exact long-range temporal correlations, power-law distributed avalanches, and amplitude bistability observed in mature human EEG data, confirming that structural synaptic remodeling is actively optimizing the brain for critical computation.<sup>1</sup>

## **Synthesizing Empowerment with Critical Dynamics**

By aligning the psychological findings of causal empowerment<sup>1</sup> with the biophysical mechanics of neural criticality<sup>1</sup>, a powerful explanatory synthesis emerges. The distinct behavioral strategies observed in children and adults are the direct psychological manifestations of their underlying physical network states.

### **The Supercritical Child and the Drive for Variability**

In the Star Machine experiments, children in undirected "play" contexts overwhelmingly abandoned controllable empowerment in favor of pure, random variability.<sup>1</sup> This behavior is the psychological shadow of the supercritical brain. Because the childhood and adolescent cortex is excitation-dominant (high E/I) and lacks the heavy GABAergic inhibition of the mature brain, it naturally generates high levels of endogenous noise and spontaneous, cascading activity.<sup>1</sup>

A supercritical system operates with a branching ratio ( $\sigma$ ) greater than 1, meaning neural

signals exponentially amplify rather than maintaining a steady state.<sup>20</sup> This physical state natively produces high behavioral entropy. Evolutionarily, this is highly advantageous for an organism that must build its causal Bayes nets from scratch. The supercritical brain drives the child to interact with the environment in highly variable, unpredictable ways, generating the massive, diverse datasets required to initially populate the causal hypothesis space.<sup>1</sup> The child's tolerance for the "noisy TV" is a feature, not a bug; it ensures that no potential causal mechanism is overlooked during the critical windows of developmental plasticity.

## **The Near-Critical Adult and the Engineering of Control**

Conversely, the adult preference for strict "controllable variability"—the hallmark of empowerment—is physically supported by the near-critical brain.<sup>1</sup> As the E/I ratio stabilizes and the branching ratio approaches exactly  $\sigma \approx 1$ , the brain achieves maximal susceptibility and signal fidelity.<sup>20</sup> In this critical regime, the endogenous noise that plagued the adolescent brain is dampened. The mature prefrontal cortex can process the complex mutual information between precise sensorimotor actuators and environmental outcomes without the signal being corrupted by runaway excitatory cascades.<sup>1</sup>

This critical state grants the adult an unparalleled dynamic range, vividly demonstrated by state-dependent adaptability.<sup>1</sup> When a mature individual transitions from a resting state to an active, goal-directed task (e.g., opening the eyes to process new visual data), the brain exhibits a massive, rapid shift. It deliberately plunges its low-frequency networks into an inhibition-dominant, subcritical state.<sup>1</sup> This aggressive, top-down suppression of the default network clears the computational slate, allowing the individual to focus entirely on the precise mechanics of the immediate causal intervention.<sup>1</sup> The adult's capacity to forcefully dictate these subcritical shifts, exploit known causal models, and engineer artifacts that guarantee empowerment is the ultimate realization of biological criticality.<sup>1</sup>

## **Embodying Empowerment: The Gastric Analogue Spacetime Metric**

While neural criticality provides the necessary cortical hardware for calculating mutual information and constructing abstract causal models, the evaluation of empowerment is not a disembodied, purely cerebral process. The subjective experience of high empowerment—often described psychologically as the state of "flow" or total cognitive immersion<sup>1</sup>—is inextricably tethered to the physical homeostasis of the body. To fully comprehend how the critical brain evaluates its causal efficacy, the peripheral autonomic nervous system must be integrated into the computational architecture.

### **The Stomach as a Relativistic Medium**

Recent theoretical advancements in biological physics have revolutionized our understanding of the gastrointestinal tract, moving beyond simple mechanical models to describe the

stomach as a highly complex, autonomous bioelectrical organ.<sup>1</sup> This framework applies the principles of analogue gravity—a field pioneered to study astrophysical phenomena like black hole thermodynamics using moving fluid media—to visceral electrophysiology.<sup>1</sup>

The human stomach is paced by a basal electrical rhythm known as the gastric slow wave.<sup>1</sup> Operating at an exceptionally low frequency of approximately 0.05 Hz, this bioelectrical pulse is generated by the Interstitial Cells of Cajal (ICC) and dictates the precise timing, velocity, and force of gastric peristalsis.<sup>1</sup> Under the analogue gravity framework, the physical smooth muscle of the stomach wall functions as an "effective spacetime metric," and the bioelectrical gastric slow wave propagates through this medium as a massless scalar field (akin to a photon propagating through curved space).<sup>1</sup>

The foundational governing equation for this biological metric is:

$$\frac{\partial^2 u}{\partial t^2} = c(x)^2 \frac{\partial^2 u}{\partial x^2}$$

where  $u(x, t)$  represents the amplitude of the gastric slow wave modeled as a Gaussian pulse, and  $c(x)$  represents the highly critical, location-dependent propagation speed of the wave through the gastric medium.<sup>1</sup>

Crucially, the stomach is not a uniform conductor. The healthy gastric medium possesses an intrinsic topology where the wave speed  $c(x)$  dictates the localized "curvature" of the effective biological spacetime. High-resolution electrogastronomy reveals a highly structured terrain: the wave originates in the proximal stomach at approximately  $6.0 \text{ mm/s}$ , decelerates to  $3.0 \text{ mm/s}$  in the transitional regions, and accelerates back to  $5.9 \text{ mm/s}$  as it approaches the pylorus.<sup>1</sup>

## Vagal Tuning: The Somatic Reward of Causal Control

The parameters governing this biological spacetime are highly plastic. The localized wave speed  $c(x)$  is continuously updated and "tuned" by the central nervous system via the vagus nerve, establishing the Gut-Brain Axis (GBA) as a unified computational circuit.<sup>1</sup>

This is the exact physiological mechanism through which the brain evaluates empowerment. When an adult agent successfully constructs an accurate causal model and executes a highly empowering intervention, the mature, near-critical prefrontal cortex (PFC) generates a pristine, high-fidelity inhibitory signal.<sup>1</sup> This signal projects downward, stabilizing the Dorsal Motor Nucleus of the Vagus (DMV).<sup>1</sup>

We can mathematically define this vagal tuning parameter as  $V(t)$ , which acts as a real-time

modulatory variable derived from the cortical E/I balance. The functional wave speed of the stomach thus becomes:

$$c(x, t) = c_{intrinsic}(x) + f(V(t))$$

where  $c_{intrinsic}(x)$  is the baseline cellular propagation speed, and  $f(V(t))$  is the dynamic vagal modulation.<sup>1</sup>

When an agent operates with high empowerment, the stable vagal tone acts as a homeostatic smoothing mechanism. It dynamically adjusts  $c(x, t)$  to ensure that the acoustic metric remains continuously positive and completely free of singularities.<sup>1</sup> The 0.05 Hz gastric slow wave propagates flawlessly, and the physical digestion of nutrients proceeds with perfect electromechanical coupling.

Furthermore, this flawless visceral metric feeds back into the brain. Through phase-amplitude coupling (PAC), the stable 0.05 Hz gastric rhythm acts as a massive basal physiological scaffold, phase-locking with the brain's faster alpha and theta oscillations.<sup>1</sup> This trans-organ synchronization optimizes cognitive vigilance and anchors the psychological sensation of flow, proving that the realization of empowerment is a whole-body phenomenon.<sup>1</sup>

## Pathological Spacetime: Disempowerment and the Collapse of Agency

The profound interconnection between causal learning, neural criticality, and visceral spacetime is most powerfully validated by examining its failure modes. When human development is arrested, or when an agent is placed in an environment devoid of controllable variance, the integrated system undergoes a catastrophic physical and psychological collapse.<sup>1</sup>

### Analogue Event Horizons and Clinical Dysrhythmia

If the prefrontal cortex fails to achieve near-criticality during the adolescent transition—perhaps due to genetic diathesis, chronic stress, or neurodevelopmental delays that halt the pruning of excitatory synapses—the brain remains trapped in a pathological, supercritical state.<sup>1</sup> This persistent supercriticality prevents the construction of stable causal models, as the excessive neural noise washes out the precise mutual information required for empowerment gain.<sup>1</sup>

Deprived of a mature, critical controller, the top-down vagal tuning parameter  $V(t)$  becomes highly erratic or chronically suppressed. Without consistent, high-fidelity vagal support, the elasticity and excitability of the ICC networks in the gut begin to fail.<sup>1</sup> The effective spacetime metric experiences drastic, localized drops in curvature. When the physiological degradation is

severe enough, the wave speed is pathologically reduced to zero ( $c(x) \rightarrow 0$ ).<sup>1</sup>

In the analogue gravity framework, this coordinate constitutes an "analogue event horizon".<sup>1</sup> The 0.05 Hz bioelectrical pulse becomes trapped by the pathological curvature of the gastric medium, entirely unable to propagate distally. The electromechanical coupling of the stomach halts instantly. Clinically, this localized collapse of spacetime manifests as severe conduction blocks, intractable dysrhythmias, and debilitating motility disorders such as gastroparesis, characterized by severe nausea and the inability to digest food.<sup>1</sup>

## Hyper-Coupling and the Dimensional Signature of Psychopathology

The formation of an analogue event horizon within the viscera does not occur in a vacuum; it initiates a devastating ascending feedback loop that shatters the psychological architecture of the agent.<sup>1</sup> When the bioelectrical pulse is trapped at the event horizon boundary, it triggers a massive, uncoordinated burst of vagal afferent firing—a biological equivalent to Hawking radiation.<sup>1</sup>

This overwhelming distress signal floods the Nucleus Tractus Solitarius (NTS) and forcefully ascends into the amygdala, anterior insula, and prefrontal cortex.<sup>1</sup> Bombarded by this high-amplitude noise, the delicate E/I balance of the cortex is entirely obliterated. Paradoxically, rather than decoupling from the failing organ, the brain is forcibly dragged into an abnormally strong phase-locking with the pathological gut rhythm.

Large-scale machine learning analyses of resting-state fMRI paired with high-density electrogastrography reveal that this specific phenomenon—hyper-coupling between the stomach and the frontoparietal control networks—is the foundational dimensional signature of severe psychological distress.<sup>1</sup> This aberrant hyper-coupling correlates overwhelmingly with clinical trait anxiety, severe depression, and executive dysfunction.<sup>1</sup>

Psychologically, the agent experiences this physiological collapse as an absolute loss of empowerment and agency. The hyper-coupled cortical networks lose their dynamic range and their susceptibility; they become too rigid to process subtle environmental cues or construct new causal models to escape the stressor.<sup>1</sup> The individual is trapped in a state of learned helplessness. Thus, the psychological inability to gain empowerment is inextricably tied to the physical collapse of biological spacetime.

Biological Domain	Healthy Matured State (High Empowerment)	Pathological State (Disempowerment / Stress)
Brain E/I Balance ( $\alpha/\theta$ )	Near-Critical (Balanced E/I, High DFA)	Supercritical (High E/I, Low Stability, Low DFA)

<b>Vagal Control Signal ( <math>V(t)</math> )</b>	High tone, high fidelity, adaptable	Low tone, highly erratic, suppressed
<b>Gastric Acoustic Metric ( <math>c(x)</math> )</b>	Smooth curvature, variable $c(x) > 0$	Collapse of $c(x) \rightarrow 0$ at specific loci
<b>Spacetime Topology</b>	Continuous, rhythmic wave propagation	Analogue Event Horizons (Conduction Blocks)
<b>Gut-Brain Coupling</b>	Subtle, state-dependent, flexible	Hyper-coupled, locked to pathological rhythm
<b>Clinical Presentation</b>	Autonomic resilience, optimal causal learning	Trait anxiety, depression, severe gastroparesis

Table 3: Comparison of integrated physiological and psychological parameters across the Gut-Brain Axis in healthy, empowered states versus pathological, disempowered states.<sup>1</sup>

## Therapeutic Interventions and Artificial Intelligence

Understanding that human causal learning and empowerment are grounded in the physical mechanics of neural criticality and visceral spacetime opens revolutionary avenues for both medical therapeutics and the development of advanced artificial intelligence.<sup>1</sup>

### Electroceutical Spacetime Repair

When an individual is locked in a hyper-coupled, supercritical state, traditional psychological interventions (such as cognitive behavioral therapies attempting to verbally rebuild causal models) often fail, as the cortical networks lack the physical susceptibility required to integrate new information.<sup>1</sup> In these instances, intervention must directly target the physical parameters of the metric.

Vagus Nerve Stimulation (VNS) has emerged as a potent, bidirectional electroceutical tool capable of artificially repairing the biological spacetime.<sup>1</sup> By delivering algorithmically precise

electrical pulses directly to the cervical vagus nerve, VNS bypasses the dysfunctional prefrontal controller and artificially injects the missing tuning parameter  $f(V(t))$  into the gut.<sup>1</sup> Pre-clinical mapping demonstrates that acute VNS significantly alters the localized values of  $c(x)$ , increasing propagation velocity and inducing massive relaxation of the pyloric sphincter. This artificial tuning smooths out the pathological curvature, effectively dissolving the analogue event horizons and restoring forward mechanical motility.<sup>1</sup>

Simultaneously, the ascending electrical signals generated by VNS act upon the brainstem to forcibly recalibrate the cortical E/I balance. VNS triggers the release of central neuromodulators that vastly upregulate GABAergic inhibition while dampening excitatory amino acids like glutamate.<sup>1</sup> This massive inhibitory influx manually pushes the supercritical, anxious brain back down toward the critical phase transition boundary.<sup>1</sup> By repairing both the neural hardware and the visceral metric simultaneously, VNS restores the agent's dynamic range, granting the individual the requisite physiological stability to once again pursue empowerment and active causal exploration.<sup>1</sup>

## Engineering Empowerment in Artificial Agents

The synthesis of these biological frameworks also provides the ultimate blueprint for solving the fundamental limitations of modern artificial intelligence. Current large language models (LLMs) and standard deep reinforcement learning (RL) systems possess vast associative pattern-matching capabilities, but they entirely lack genuine causal inference.<sup>1</sup> They remain passive consumers of human-generated data, incapable of formulating interventions or navigating the "noisy TV" problem in unconstrained environments.<sup>1</sup>

To achieve human-like artificial general intelligence, AI architectures must be redesigned to mimic the biological ontogeny outlined in this report. First, RL agents must be endowed with intrinsic epistemic motivations—specifically empowerment, and its newly formulated mathematical mirror, "plasticity" (the generalized directed information capturing how an agent is influenced by its observations).<sup>1</sup> By programming agents to explicitly maximize the mutual information between their actuators and sensors, they will naturally seek out controllable variability, constructing accurate causal world models without the need for external, human-programmed reward functions.<sup>1</sup>

Secondly, the underlying neural network architectures of these agents must be designed to natively support self-organized criticality. Rather than relying on static, back-propagated weights, artificial networks should utilize dynamic excitation-inhibition balancing mechanisms that allow the system to transition between supercritical (high-variance, exploratory) and near-critical (high-fidelity, exploitative) regimes.<sup>1</sup> Endowing AI with the capacity for phase transitions will grant artificial systems the unprecedented susceptibility and dynamic range that biological agents utilize to master the causal structure of the universe.<sup>1</sup>

## Conclusion

The developmental trajectory of human cognition is not a localized phenomenon occurring exclusively within the abstract algorithms of the mind; it is the grand, systematic calibration of a vast, interdependent bio-physical control system. By exhaustively synthesizing the psychological dynamics of empowerment gain and causal model construction with the relativistic mechanics of neural criticality and gastric analogue gravity, a profound, unified framework of human maturation is realized.

Causal learning is the fundamental mechanism by which a biological agent maximizes its agency over the physical world. During the early epochs of childhood and adolescence, the brain's supercritical, excitation-dominant architecture purposefully drives the agent toward "pure variability." This physical state natively generates high behavioral entropy, facilitating the rapid, stochastic exploration required to map the boundaries of the global causal landscape, albeit at the cost of transient autonomic volatility and vulnerability.

As the organism matures into adulthood, the aggressive structural regulation of the excitation-inhibition balance pulls the cerebral cortex to a state of self-organized criticality. This highly optimized, near-critical boundary grants the adult brain the immense computational susceptibility, signal fidelity, and dynamic range required to compute the exact mutual information between specific actions and environmental outcomes. This physical transition actualizes the psychological shift toward "controllable variability," empowering the adult to engineer complex causal interventions and execute goal-directed workflows.

Crucially, this cognitive mastery is physically embodied and evaluated by the peripheral autonomic system. High-fidelity causal modeling allows the mature prefrontal cortex to exert precise, stable vagal tone. This tone acts as a master homeostatic tuning parameter, continually smoothing the biological effective spacetime metric of the stomach wall. The flawless, frictionless propagation of the gastric slow wave provides a continuous, rhythmic somatic scaffold that phase-locks with the higher-order cortical networks. This deep trans-organ resonance provides the physiological foundation for the subjective experience of cognitive flow, sustained vigilance, and true embodied agency.

Conversely, failures in this integrated system—whether driven by chronic disempowerment, stress, or arrested neurodevelopment—result in catastrophic topological collapse. The loss of critical vagal tuning causes the visceral metric to fracture, forming analogue event horizons that trap bioelectrical energy, halt digestion, and transmit massive afferent distress signals to the brain. This ascending noise forcibly locks the cortex into a rigid, hyper-coupled supercritical state, physically manifesting the cognitive paralysis and emotional despair of severe psychiatric illness.

Ultimately, the transition to a healthy, functional adulthood represents the total mastery of biological analogue gravity. Achieving true psychological empowerment is inextricably tied to the realization of optimal neural criticality, allowing the human agent to flawlessly command the

physical topology of both its internal visceral spacetime and the external causal world.

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