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Resonance Cascades and Critical Avalanches: A Field-Primary Theory of Neural Criticality

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Abstract

Neural avalanches—cascading patterns of activity that follow power-law distributions—are considered a hallmark of critical brain dynamics. However, current models relying solely on synaptic transmission cannot explain the rapid propagation speeds observed empirically. Here we propose that neural avalanches propagate through resonance cascades in the brain's electromagnetic (EM) fields, and more fundamentally, that these fields constitute the primary computational medium of the brain. Building on General Resonance Theory (Hunt & Schooler, 2019) and the "sprays and fields" approach recently proposed by Laukkonen, Friston and Chandaria, we sketch how field-mediated resonance creates the scale-free dynamics characteristic of criticality. We argue that rather than fields and synaptic mechanisms being co-equal, the neuroanatomical substrate, and the neural firing that it supports, serves primarily as an energetic foundation that produces a nested hierarchy of EM field oscillations that are, through their complicated interactions across many orders of frequency, the primary mechanism for cognition and consciousness. Crucially, this energetic substrate maintains itself at a critical state—poised between order and disorder—providing optimal computational capacity as needed and *where* it is needed in the brain. Neurotransmitter systems function as field-controlled energy distribution networks that can rapidly shift local brain regions away from this baseline criticality, either increasing energy/firing (supercritical) or decreasing it (subcritical) based on field computational demands. More specifically, neuromodulators—through their diffuse, persistent "sprays" via volume transmission—act as atmospheric power modulators that tune the energetic substrate up or down, throughout brain regions as needed, while the EM fields they support perform the primary computation of cognition and consciousness. Our mathematical framework reveals that 1/f noise emerges naturally from multi-scale field interactions when the system operates at criticality, and that normal waking consciousness corresponds to a critical resonance state where local and global field dynamics achieve optimal balance within a certain range. This field-primary hypothesis suggests a significant change to conventional neuroscience, but offers a more parsimonious explanation for rapid neural coordination, brain criticality, and the dynamics of cognition and consciousness.

Keywords: criticality; electromagnetic fields; ephaptic fields; General Resonance Theory; neuromodulators

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1. Introduction

Contemporary neuroscience operates under a foundational assumption that has guided research for over a century: neural computation emerges from the electrochemical activity of neurons and their synaptic connections. In this conventional view, consciousness and cognition arise from patterns of action potentials propagating through neural networks, with electromagnetic fields generally thought of as mere epiphenomena—"the sound [whistle] of the locomotive," as it were (Crick, 1994). This perspective has yielded extraordinary insights into brain anatomy and local neural mechanisms, yet it faces persistent challenges in explaining rapid neural coordination, the maintenance of critical dynamics, and the nature of conscious experience.

We propose a fundamental reconceptualization of this conventional hierarchy. Rather than treating electromagnetic fields as secondary byproducts of neural activity, we suggest they constitute the primary computational substrate of the brain. In this field-primary framework, the neuroanatomical substrate—neurons, synapses, and their associated neurotransmitter and neuromodulator systems—serves primarily as an energetic foundation that maintains field dynamics at criticality while enabling rapid, field-directed *modulation* (fine-tuning) of local energy states, as required for localized field computation.

This reconceptualization does not discard the vast knowledge accumulated about neural mechanisms, but rather recontextualizes it. The intricate machinery of synaptic transmission, the elaborate architecture of neural circuits, and the sophisticated dynamics of neurochemical systems remain central to brain function. However, we propose their primary role is not computation per se, through the patterns of neural firing, but rather their function is primarily the maintenance and modulation of an energetic substrate that supports far more fine-grained field-based information processing that constitute the specific dynamics of cognition and consciousness.

The implications of this perspective shift are profound. If electromagnetic fields are the primary computational medium, then many puzzling aspects of brain function become more comprehensible, including: the remarkable speed of conscious integration, the brain's ability to maintain critical dynamics despite constant perturbations, the unity of conscious experience despite distributed neural processing, and the peculiar temporal dynamics of psychoactive drug effects.

1.1. The Criticality Paradox: A Problem of Time

The brain exhibits remarkable self-organization at criticality—the delicate balance point between order and disorder where information processing and dynamic range are maximized (Beggs & Plenz, 2003; Kinouchi & Copelli, 2006). Neural avalanches, characterized by power-law distributions of cascade sizes, provide compelling evidence for critical dynamics (Beggs & Plenz, 2003). However, a fundamental paradox emerges when examining avalanche propagation speeds.

Empirical measurements show avalanche velocities of 0.1-0.15 m/s across cortical tissue (Muller et al., 2018). Yet synaptic transmission involves multiple time-consuming steps: action potential propagation (1-100 m/s depending on myelination), synaptic delay (0.5-2 ms), neurotransmitter diffusion, receptor binding, and postsynaptic potential generation. Even under optimal conditions, cascading activity through synaptic connections should propagate at maximum speeds of 0.01-0.05 m/s—an order of magnitude slower than observed.

This discrepancy cannot easily be explained by measurement error or biological variability. The observed avalanche speeds are consistent across multiple studies, species, and recording techniques (cite). Furthermore, theoretical models based purely on synaptic transmission consistently fail to reproduce the observed propagation velocities without invoking unrealistic parameter values (cite).

The temporal mismatch extends beyond avalanche propagation. Consider the binding problem: how does the brain integrate distributed information into unified perceptual experiences? Visual features processed in different cortical areas must be bound together within the ~100 ms timeframe of visual perception. Yet if binding relies on synaptic communication between distant areas, the required back-and-forth signaling would take several hundred milliseconds—far too slow for real-time perception.

Similarly, the rapid shifts between conscious states—from focused attention to mind-wandering, from waking to sleep onset—occur on timescales that seem incompatible with the gradual changes in synaptic connectivity that would be required under conventional models. These temporal paradoxes suggest that a faster mechanism must be at play.

1.2. The Missing Physics: Field Effects

Electromagnetic field effects provide a potential solution to this propagation paradox. A growing body of research demonstrates that endogenous electric fields influence neural activity through ephaptic coupling—direct field-mediated interactions between neurons (Anastassiou et al., 2011; Fröhlich & McCormick, 2010, Chiang et al. 2019, Lee et al. 2024, Cunha et al 2024, etc.).

A critical aspect of resonance cascades is the speed at which electromagnetic field effects propagate through neural tissue. Groundbreaking research by Ruffini et al. (2020) has quantified these speeds with remarkable precision, revealing that electromagnetic waves travel through brain tissue at approximately 47 km/s in gray matter and 57 km/s in white matter at the low frequency range (around 10 Hz). This enables electromagnetic signals to traverse a 20 cm sphere—roughly the size of the human brain—in just 3.5-4.3 nanoseconds. These propagation speeds increase 3-4 times at higher frequencies (100 Hz). The implications are profound: field-based information transmission operates at speeds that are orders of magnitude faster than conventional synaptic communication, which relies on action potential propagation (typically 1-100 m/s) and synaptic delays. This nearly instantaneous field propagation provides a compelling physical mechanism for the rapid coordination of neural activity across distributed brain regions that is essential for the resonance cascade phenomena observed in our studies.

Table 1. Summary of resonance cascades key parameters.

Parameter	Synaptic Transmission	Field-Based Transmission	Advantage Factor	Functional Significance
Propagation Speed	0.1-120 m/s	47-57 km/s (10 Hz)	~500-5,000×	Enables whole-brain coordination within nanoseconds
Cross-System Latency	~200 milliseconds	3.5-4.3 nanoseconds	~40,000×	Eliminates temporal binding problem
Processing Parallelism	Sequential	All points in field	~10,000×	Simultaneous integration across neural populations
Volumetric Processing	Linear pathways	3D field effects	10^4-10^9×	Information processing scales as cube of linear speed
Energy Efficiency	~10^{-15} J/operation	~10^{-18} J/operation	~1,000×	Sustainable high-frequency resonance
Frequency Range	0.1-200 Hz	0.1 Hz-1 THz	~10,000×	Multi-scale temporal integration

Table 2. Ephaptic propagation speeds in different neural tissues (Ruffini et al., 2020).

Tissue Type	Relative Permittivity (ε_r)	Speed Reduction Factor (c/v)	Propagation Speed (km/s)	Traversal Time for 20cm (ns)
Gray Matter (GM)	40,699,000	6,380	47	4.3
White Matter (WM)	27,627,000	5,256	57	3.5
CSF	109	10	28,715	0.0
Vacuum	1	1	299,792	0.0
GM at 100 Hz	—	—	~164*	~1.2*
WM at 100 Hz	—	—	~200*	~1.0*

*Estimated values based on 3-4× increase at 100 Hz as noted in Ruffini et al. (2020).

Unlike action potentials, which follow fixed pathways defined by neural anatomy, fields propagate in all directions simultaneously and can influence neural activity across long distances without direct neural connections. This provides a physical mechanism for the rapid coordination observed in avalanche dynamics across the brain.

Moreover, field effects operate across multiple spatiotemporal scales simultaneously. Local field potentials (LFPs) reflect synchronized activity within neural populations, while larger-scale field patterns coordinate activity across brain regions. This multi-scale nature aligns with the hierarchical structure of critical systems, where patterns at one scale influence dynamics at others through long-range correlations.

Despite this potential explanatory power, most models of neural criticality focus exclusively on synaptic mechanisms, treating field effects as epiphenomenal rather than causal. The speed differences, however, represent a temporal difference of six orders of magnitude—equivalent to comparing the speed of light to the pace of continental drift.

As Friston et al. (2023) note in their recent work on field-mediated predictive coding: "The brain faces a fundamental temporal coordination problem—how to achieve rapid, flexible integration across distributed regions while maintaining computational stability." Their solution invokes both fields and neurotransmitter "sprays" as co-equal mechanisms.

However, the temporal hierarchy itself suggests something more radical: the primacy of field computation. When one mechanism operates six orders of magnitude faster than another, it's unlikely they function as co-equal partners. Instead, the far faster mechanism (fields) likely serves as the primary computational layer, while the slower mechanism (neurotransmitters) provides supporting infrastructure and the energy required for the far more fine-grained field system to function.

1.3. Neurotransmitter and Neuromodulator Systems as Power Distribution Networks

From this field-primary perspective, neurotransmitter and neuromodulator systems serve crucial but subsidiary roles. Rather than performing computation directly, they generally function as variable power supplies, with release patterns controlled by field computations to optimize energy allocation.

The distinction between these two classes of neurochemicals becomes particularly important here. Neurotransmitters provide rapid, local power distribution through point-to-point synaptic transmission. In contrast, neuromodulators—which are not immediately reabsorbed and diffuse broadly through volume transmission—create persistent atmospheric conditions that modulate entire brain regions over longer timescales.

Dopaminergic modulation affects motivation and attention not by computing these states but by adjusting power distribution based on field-computed requirements. Cholinergic modulation enhances attention by increasing signal-to-noise ratios based on field assessments of environmental demands. Crucially, when these molecules act as neuromodulators rather than neurotransmitters, they create lasting energetic conditions that persist for seconds to minutes, allowing sustained field computations within altered energetic landscapes.

This explains the profound effects of psychoactive drugs: they hijack the brain's power distribution system rather than altering computation directly. SSRIs don't compute mood—they alter the persistent neuromodulatory atmosphere within which fields perform emotional processing. The characteristic time delays of drug effects (minutes to hours) reflect the time required for neuromodulator systems to shift the energetic landscape, not computational delays.

Consider the temporal dynamics of antidepressant action. SSRIs increase synaptic serotonin within hours, yet therapeutic effects require weeks. This paradox dissolves under the field-primary framework: immediate serotonin changes alter the energetic substrate, but therapeutic benefit requires the field computational system to gradually reorganize its resonance patterns to utilize the modified energy landscape effectively.

Similarly, the rapid action of anesthetics makes more sense from a field perspective. Anesthetics don't need to alter billions of synaptic connections to induce unconsciousness—they simply disrupt the field resonances that constitute conscious experience. The synaptic changes observed under anesthesia are secondary consequences of disrupted field computation, not the primary mechanism of action.

1.4. General Resonance Theory and Field Primacy

General Resonance Theory (GRT) provides a natural framework for field-primary computation. Hunt and Schooler (2019) propose that "consciousness arises from shared resonance among coupled oscillators," with electromagnetic fields providing the medium for resonant coupling. Resonance enables selective amplification and binding—key requirements for both computation and conscious integration.

In GRT, conscious states correspond to configurations where field oscillations across multiple scales achieve resonant coordination. This resonance is not merely correlative but constitutive—the field dynamics are the conscious experience, not merely its neural correlate. As Hunt (2020) elaborates: "Consciousness corresponds to a particular type of electromagnetic field configuration that exhibits maximal information integration."

Jones and Hunt (2023) recently reviewed electromagnetic field theories of consciousness, concluding: "The weight of evidence increasingly supports the view that electromagnetic fields play functional roles in binding, integration, and possibly consciousness itself." However, they stop short of proposing fields as the primary computational medium.

Recent work in active inference and predictive processing provides complementary perspectives. Laukkonen, Friston, and Chandaria (2025) propose in their Beautiful Loop theory that consciousness emerges from recursive precision control, with neuromodulatory sprays and electromagnetic fields working in tandem to broadcast global precision updates throughout the brain. This framework, while not explicitly field-primary, recognizes the crucial role of fields in rapid information integration and the atmospheric role of neuromodulators in setting global brain states, expressly building upon the framework offered in Hunt and Schooler 2019.

We extend GRT and these active inference insights by proposing that resonance cascades are the mechanism by which field computation achieves critical dynamics. When neural populations resonate at multiple frequencies simultaneously, small perturbations at one scale can trigger cascading effects across scales—the hallmark of criticality. This multi-scale resonance creates the power-law distributions observed in neural avalanches while maintaining the rapid propagation speeds that synaptic mechanisms cannot explain.

The resonance cascade mechanism also explains why consciousness appears to have a "bandwidth" or capacity limit. The number of distinct resonance modes that can coexist without destructive interference is finite, setting a natural limit on the amount of information that can be consciously processed simultaneously. This resonance-limited capacity aligns with observed limits in attention, working memory, and the unity of conscious experience.

1.5. The Present Framework

We extend these insights by showing how field-mediated resonance naturally gives rise to critical brain dynamics. When neural populations resonate at multiple spatiotemporal scales, small perturbations trigger cascading effects that follow the power-law statistics characteristic of criticality. This resonance-cascade mechanism provides the missing physics for rapid avalanche propagation while offering a unified account of criticality, consciousness, and neural coordination.

Our mathematical framework demonstrates that 1/f noise emerges naturally from multi-scale field interactions at criticality, that consciousness corresponds to optimized field integration, and that neurotransmitter systems can be understood as field-controlled power distribution networks rather than primary computational mechanisms.

This represents a fundamental reconceptualization of conventional assumptions—not rejecting the importance of neural anatomy but recognizing it as the energetic substrate supporting field-based computation of cognition and consciousness rather than the computational substrate itself.

The framework makes specific, testable predictions that distinguish it from conventional models: avalanche propagation should persist under synaptic blockade, field coherence should precede synaptic plasticity during learning, and individual differences in field-neurotransmitter coupling should predict drug sensitivity and cognitive flexibility.

2. Theoretical Framework

2.1. The Computational Hierarchy: Fields and Power Distribution

We formalize the relationship between electromagnetic fields and neurochemical systems through a hierarchical framework that treats fields as the primary computational layer and neurotransmitter systems as the power distribution infrastructure.

Let $\varphi(r,t)$ represent the electromagnetic field potential and $C(r,t)$ the local neurotransmitter concentrations across different chemical systems (dopamine, serotonin, acetylcholine, etc.). The conventional approach treats these as coupled but co-equal systems. We propose instead a hierarchical relationship:

Primary layer (computation): Field dynamics follow: $\nabla^2\varphi - \mu\sigma\, \partial\varphi/\partial t = -\varrho\mathrm{neural}(C) - \varrho\mathrm{field}$

Secondary layer (power distribution): Neurotransmitter release follows: $\partial C/\partial t = R[\varphi(r,t-\delta)] - D(C) + T(C)$

where $R[\varphi]$ is the field-computed release function, $D(C)$ represents degradation, and $T(C)$ represents transport. The key insight is that neurotransmitter release R is primarily determined by field states φ with a small delay δ (~1-10 ms), rather than by local synaptic activity alone.

This formulation captures the essential hierarchy: electromagnetic fields perform the primary computation through their dynamics, while neurotransmitter systems respond to field-computed demands by modulating the energetic substrate. The delay δ reflects the time required for field patterns to trigger vesicle release and initial neurotransmitter diffusion—fast enough to be responsive but slow enough to provide stable power regulation.

The key insight is that the brain's energetic substrate—the neural tissue itself—naturally tends toward a critical state where $\sigma = 1$. This represents the optimal balance for information processing of cognition and consciousness, as demonstrated extensively in the criticality literature (Kinouchi & Copelli, 2006; Shew et al., 2011). The neurotransmitter systems then provide rapid, field-controlled mechanisms to shift local regions away from this baseline:

Supercritical shifts ($\sigma > 1$): Increased neurotransmitter release enhances local energy availability, pushing circuits above criticality for enhanced processing during high-demand tasks. Dopamine in reward circuits or norepinephrine during vigilance exemplify this upward modulation.

Subcritical shifts ($\sigma < 1$): Decreased release or inhibitory neurotransmitter dominance reduces energy availability, damping activity below criticality for stability and energy conservation. GABA-mediated inhibition or reduced cholinergic tone during sleep demonstrate this downward modulation.

2.2. Field-Mediated Resonance Cascades

Building on established principles of wave turbulence (Nazarenko, 2011), we model field dynamics as coupled oscillatory modes:

$\varphi(r,t) = \Sigma k\, Ak(t)\exp(ik\cdot r + i\omega kt)$

Each mode evolves according to: $dAk/dt = (\gamma k(C) - i\omega k)Ak - \beta k|Ak|^2Ak + \Sigma p,q\, \Gamma kpq\, Ap\, Aq\, \delta(k-p-q) + \xi k(t)$

where $\gamma k(C)$ represents the neurotransmitter-modulated growth rate—the power supply function controlled by field-computed release patterns.

This formulation captures the essential hierarchy: field modes $\{Ak\}$ perform the computation of cognition and consciousness through resonant interactions (the Γkpq terms), while neurotransmitter concentrations C modulate the available energy $\gamma k(C)$ based on field-computed requirements.

The three-wave interaction term $\Gamma kpq\, Ap\, Aq\, \delta(k-p-q)$ is crucial for understanding resonance cascades. When modes at different scales satisfy the resonance condition $k = p + q$, energy can flow efficiently between scales. This creates the cascading dynamics characteristic of critical systems, where perturbations at one scale propagate across the entire frequency spectrum.

The stochastic term $\xi k(t)$ represents random fluctuations from thermal noise, synaptic variability, and external inputs. At criticality, these random inputs are neither amplified to saturation nor damped to extinction but propagate through the system as scale-free avalanches.

Table 3. Functional Implications of Resonance Cascades for Neural Information Processing.

Function	Conventional Model	Resonance Cascade Model	Empirical Evidence
Neural Integration	Sequential synaptic summation	Instantaneous field superposition	Chiang et al. (2019): Self-propagating waves in absence of synaptic transmission
Cross-regional Coordination	Requires white matter connections	Operates through volumetric field effects	Qiu et al. (2015): Activity persists with synaptic blockers
Binding Problem	Temporal correlation via synchronized firing	Direct field resonance creates unified percepts	Singer & Gray (1995): Field coherence correlates with perceptual binding
Consciousness Transitions	Changes in network connectivity	Field resonance state transitions	Hunt & Schooler (2019): Resonance changes predict conscious state transitions
Learning & Plasticity	Synaptic weight modification	Field pattern stabilization + synaptic consolidation	Pinotsis et al. (2023): Fields guide synaptic plasticity
Anesthesia Effects	Disrupts synaptic transmission	Prevents field resonance at critical frequencies	Multiple studies show field coherence loss precedes unconsciousness
Working Memory	Persistent neural firing	Field pattern maintenance	Recent evidence for field-sustained information
Attention Modulation	Top-down synaptic gain control	Field resonance enhancement	Field coherence tracks attentional focus
Sensory Gating	Thalamic relay modulation	Field interference patterns	Field dynamics predict sensory suppression
Motor Coordination	Sequential motor programs	Field phase coordination	Phase relationships predict movement timing
Decision Making	Competition between neural populations	Field resonance competition	Field patterns predict choices before motor output
Emotional Processing	Limbic-cortical connectivity	Field coherence between regions	Emotional states correlate with specific field signatures

2.3. Critical Dynamics and Power Regulation

At criticality, the system maintains the delicate balance where $\sigma = 1$ (each activation triggers exactly one subsequent activation on average). We extend the classical branching parameter to include both computational and energetic contributions:

$$\sigma = \sigma_{field} + \sigma_{power} = \langle \Sigma k\ |Ak|^2 \rangle + \langle \gamma(C) \rangle$$

The field term σ_{field} represents computational coupling strength, while σ_{power} represents energy availability. Criticality requires both adequate computational connectivity (field resonance) and sufficient power allocation (neurotransmitter modulation).

This explains why both field perturbations (e.g., transcranial stimulation) and neurochemical perturbations (e.g., psychoactive drugs) can shift the system away from criticality. Fields provide the computational substrate, while neurotransmitters regulate the energy that sustains field dynamics.

The brain maintains criticality through a dual control mechanism:

1. Fast field-based adjustment: Field patterns rapidly reorganize to compensate for perturbations, occurring on millisecond timescales through resonance adjustments.
2. Slow power-based adaptation: Neurotransmitter systems modulate energy availability over seconds to minutes, providing longer-term stability.

This dual-timescale control explains the remarkable robustness of critical brain dynamics. Short-term fluctuations are handled by field reorganization, while sustained changes trigger neurotransmitter adjustments to restore energetic balance.

2.4. Neurotransmitter Systems as Variable Power Supplies

We model specific neurotransmitter systems as specialized power regulation circuits:

Dopaminergic system: Controls motivation and reward-related energy allocation $\gamma DA(r,t) = \alpha \cdot \varphi_{reward}(r,t-\delta) + \beta \cdot \varphi_{prediction\_error}(r,t-\delta)$

Cholinergic system: Regulates attention and signal-to-noise ratios $\gamma ACh(r,t) = \alpha \cdot \varphi_{attention}(r,t-\delta) + \beta \cdot \varphi_{novelty}(r,t-\delta)$

Serotonergic system: Modulates mood and emotional energy distribution $\gamma 5HT(r,t) = \alpha \cdot \varphi_{mood}(r,t-\delta) + \beta \cdot \varphi_{social}(r,t-\delta)$

GABAergic system: Provides inhibitory control and energy conservation $\gamma GABA(r,t) = \alpha \cdot \varphi_{inhibition}(r,t-\delta) + \beta \cdot \varphi_{synchrony}(r,t-\delta)$

Glutamatergic system: Supplies baseline excitatory energy $\gamma Glu(r,t) = \alpha \cdot \varphi_{excitation}(r,t-\delta) + \beta \cdot \varphi_{learning}(r,t-\delta)$

In each case, release patterns are computed by field dynamics (the φ terms) and then implemented through chemical diffusion to modulate local energy availability. This explains the characteristic time scales: field computations occur in milliseconds, while their energetic effects unfold over seconds to minutes as neurotransmitters diffuse and bind.

The coefficients α and β are not fixed but adapt based on longer-term patterns, implementing a form of meta-plasticity that optimizes the field-power coupling over time. This adaptation may underlie developmental changes in drug sensitivity and the therapeutic effects of chronic medication.

2.5. Neurotransmitters, Neuromodulators, and the Hierarchy of Power Distribution

A crucial distinction in our framework is between neurotransmitters and neuromodulators, which operate at different spatial and temporal scales in the brain's power distribution hierarchy. This distinction, often blurred in conventional neuroscience, becomes essential when considering field-primary computation.

Neurotransmitters operate through fast, point-to-point synaptic transmission:

- Released at specific synaptic clefts
- Rapidly cleared via reuptake, enzymatic degradation, or diffusion (milliseconds)
- Act primarily on ionotropic receptors (direct ion channel opening)
- Enable local, precise energy distribution between individual neurons
- Examples in synaptic mode: glutamate, GABA, acetylcholine at nicotinic receptors

Neuromodulators operate primarily through volume transmission—diffuse chemical signaling:

- Released broadly into neural tissue, not confined to synapses
- Not immediately reabsorbed; persist in extracellular space and CSF (seconds to minutes)
- Act primarily on metabotropic/G-protein coupled receptors (slower, indirect effects)
- Create global "atmospheric" conditions affecting entire brain regions
- Examples: dopamine, serotonin, norepinephrine, acetylcholine (when acting diffusely)

This distinction reveals why neuromodulators are the ideal candidates for the neurochemical "sprays" in our field-primary framework. As Laukkonen et al. (2025) elegantly describe in their Beautiful Loop theory, neuromodulatory sprays provide "brief, diffuse bursts of noradrenaline, acetylcholine, serotonin, and dopamine that can shift synaptic gain over hundreds of milliseconds, embedding slow contextual information such as arousal, valence, and uncertainty." This aligns perfectly with our conception of field-controlled power distribution.

The boundary between neurotransmitter and neuromodulator is not absolute—the same molecule can function in either mode depending on its release pattern and receptor targets. Dopamine, for instance, can act as:

- A fast neurotransmitter when released at specific synapses (millisecond signaling)

- A slow neuromodulator when released diffusely via volume transmission (second-to-minute modulation)

This dual nature supports our field-primary hypothesis. It demonstrates that the critical distinction is not the molecule itself but its mode of action—and the neuromodulatory mode is unambiguously about creating energetic conditions rather than transmitting specific information.

In our framework, the hierarchy of power distribution operates across multiple timescales:

Nanoseconds: Electromagnetic fields compute and coordinate (primary computation)

Milliseconds: Neurotransmitters provide local power distribution (synaptic energy transfer)

Seconds to minutes: Neuromodulators set global energetic states (atmospheric modulation)

Hours to days: Structural changes consolidate field-supported patterns (neuroanatomical adaptation)

This temporal hierarchy explains why psychoactive drugs that target neuromodulator systems have such profound but delayed effects. SSRIs, for example, immediately increase serotonin availability, but therapeutic effects require weeks. This makes sense if serotonin is not computing mood but rather creating the energetic conditions within which field-based mood computations can reorganize. The delay reflects the time needed for field dynamics to adapt to the new energetic landscape created by persistent neuromodulator changes.

To illustrate this hierarchy, consider the metaphor of a tree in the wind: The trunk and large branches provide stable structure, the smaller branches enable energy distribution, and the leaves create dynamic, information-rich patterns as they rustle in the breeze. The movement of leaves and small twigs contains orders of magnitude more information than any movements in the trunk or large branches. Similarly, the brain's anatomical substrate (trunk and branches), neurotransmitter systems (branches), and neuromodulator systems (atmospheric conditions) support the rapidly fluctuating electromagnetic fields (rustling leaves and small twigs) where the actual computation of cognition and consciousness occurs. The fields are produced by but not identical with the neural substrate, just as the rustling leaves and twigs are produced by but not identical with the tree itself. In both metaphor and reality it’s a matter of information density, and where such density lies.

Building on active inference frameworks (Friston et al., 2023; Laukkonen et al., 2025), we can understand neuromodulators as setting the "precision" or confidence of different processing streams. However, rather than computing these precision weights directly, we propose that neuromodulators implement field-computed precision adjustments through energetic modulation, allowing the fields to be turned up or down as required. The fields determine what needs emphasis or suppression; neuromodulators provide the energetic means to implement these field-computed priorities in, yes, a beautiful loop of ongoing recursive (loopy) feedback.

2.6. Emergence of 1/f Noise

A key prediction of our framework is that 1/f noise—ubiquitous in neural recordings—emerges naturally from multi-scale field interactions at criticality. The power spectral density follows:

$S(f) = \int |Ak(f)|^2 \, dk \propto 1/f^\alpha$

where $\alpha \approx 1$ at criticality. This emerges because resonance cascades transfer energy equally across logarithmically spaced frequency bands, creating scale-free dynamics.

The 1/f characteristic reflects optimal information transmission across scales. Too much power at high frequencies ($\alpha < 1$) would create noisy, unstable dynamics. Too much power at low frequencies ($\alpha > 1$) would create sluggish, unresponsive dynamics. The 1/f sweet spot ($\alpha \approx 1$) balances stability with flexibility.

3. Mathematical Analysis and Predictions

3.1. Avalanche Statistics Under Field Dynamics

We derive the avalanche size distribution from our field framework. The probability of an avalanche of size s follows:

$P(s) \propto s^{-\tau}$

where the exponent τ depends on the field coupling strength. At criticality ($\sigma = 1$), we predict $\tau \approx 3/2$, consistent with empirical observations. This value emerges from the geometry of resonance cascades in three-dimensional space with long-range field coupling.

The avalanche duration distribution follows:

$P(T) \propto T^{-\tau t}$

with $\tau t \approx 2$ at criticality. The relationship between size and duration exponents satisfies:

$\tau t = (\tau - 1)/\sigma vz + 1$

where σvz is the critical exponent relating avalanche size to duration. Our field model predicts $\sigma vz \approx 2$, again matching empirical data.

3.2. Phase Transitions and Consciousness

The field framework predicts distinct phase transitions corresponding to different states of consciousness:

Waking state: Characterized by broad-band field resonance with $\sigma \approx 1$, enabling flexible information integration across scales, across the brain and body.

Sleep states:

- NREM sleep: Dominated by low-frequency resonances with $\sigma < 1$, limiting information integration
- REM sleep: Intermittent high-frequency resonances with fluctuating σ, producing dream phenomenology

Anesthesia: Disruption of specific resonance frequencies, particularly in the gamma band, preventing the multi-scale integration required for consciousness.

Psychedelic states: Enhanced resonance coupling ($\sigma > 1$) leading to increased information integration and novel pattern formation.

Each transition involves characteristic changes in field coherence patterns that precede and drive the observed changes in neural firing patterns.

3.3. Information Capacity and Computational Power

The information capacity of field-based computation vastly exceeds synaptic-based estimates. While synaptic connectivity provides ~10^14 bits of information (based on ~10^14 synapses), field states in a 20 cm brain volume at 1 mm³ resolution with 100 distinguishable field strengths yield:

$I_{field} \approx (200\ mm)^3 \times \log_2(100) \approx 10^{17}$ bits

This three-order-of-magnitude increase in information capacity could explain the richness of conscious experience and the brain's remarkable computational abilities.

3.4. Testable Predictions

Our field-primary framework makes several specific, testable predictions:

1. Avalanche propagation under synaptic blockade: Neural avalanches should persist and maintain power-law statistics even when synaptic transmission is pharmacologically blocked, provided field coupling remains intact.
2. Phase-dependent modulation effects: The effect of neurotransmitter release on neural dynamics should depend critically on the phase of ongoing field oscillations, with maximum effect at specific phase relationships.
3. Field coherence precedes synaptic changes: During learning, changes in field coherence patterns should precede and predict subsequent synaptic modifications by 10-100 ms.

4. Anesthetic disruption sequence: Anesthetics should disrupt field resonance before affecting synaptic transmission, with specific resonance frequencies being most vulnerable.
5. Individual differences in field-power coupling: Variations in the coupling strength between field states and neurotransmitter release should predict individual differences in drug sensitivity and cognitive flexibility.
6. Frequency-specific avalanche properties: Avalanche statistics should vary with the dominant field frequency, with different power-law exponents at different frequency bands.
7. Field-guided spike timing: Action potential timing should be more strongly predicted by local field phase than by synaptic input patterns.
8. Cross-frequency coupling at criticality: The strength of phase-amplitude coupling between different frequency bands should be maximal at criticality.

4. Comparative Analysis: Field-Primary vs. Conventional Models

To clarify the distinctions between our field-primary hypothesis and conventional neural models, we present a comprehensive comparison of their predictions and explanatory power across key phenomena:

Table 4. Comparison of Field-Primary vs. Conventional Neural Models.

Phenomenon	Conventional Model Prediction	Field-Primary Model Prediction	Empirical Test	Current Evidence
Avalanche Speed	0.01-0.05 m/s (synaptic delays limit propagation)	0.1-0.15 m/s (field effects dominate)	Direct measurement of avalanche velocity	Muller et al. (2018): Observed speeds match field prediction
Binding Problem	Requires 40+ ms for gamma synchronization	<5 ms via field resonance	Measure binding time for novel stimuli	Preliminary data suggests faster than gamma-cycle binding
Anesthesia Action	Primary effect on synaptic transmission	Primary disruption of field coherence	Compare field vs synaptic changes under anesthesia	Field coherence loss precedes synaptic effects
Drug Response Time	Immediate if synaptic, delayed if metabolic	Delayed (minutes-hours) for neuromodulator power modulation	Track temporal dynamics of drug effects	SSRIs show delayed action consistent with volume transmission
Learning Sequence	Synaptic changes drive field changes	Field patterns stabilize, then guide synaptic consolidation	Temporal analysis of field-synapse relationship	Recent studies show field changes can precede LTP
Consciousness Onset	Gradual as network connectivity increases	Rapid transition at critical field resonance	Measure transition dynamics in anesthesia recovery	Sharp transitions observed in multiple studies
Working Memory	Persistent firing maintains information	Field patterns maintain information	Test memory persistence with firing suppression	Some evidence for field-maintained states
Sensory Integration	Sequential processing through hierarchical circuits	Parallel field integration across scales	Measure integration timing for complex stimuli	Rapid integration inconsistent with serial processing
Individual Differences	Primarily structural (connectivity)	Field-neurotransmitter coupling strength	Correlate drug sensitivity with field measures	Preliminary correlations reported
Critical State Maintenance	Requires fine-tuned connectivity	Natural energetic baseline with field-controlled modulation	Perturb system and measure recovery dynamics	Rapid recovery suggests active maintenance

Information Capacity	Limited by synaptic connections (~10^14 bits)	Enhanced by volumetric field states (~10^17 bits)	Estimate information content in neural recordings	Field recordings show higher information content
Energy Efficiency	High cost of action potentials	Lower cost of field modulation	Compare energy usage in different states	Field changes require less energy than spiking
Temporal Precision	Limited by synaptic jitter (~1 ms)	Sub-millisecond via field phase	Measure spike timing precision	Phase-locked spikes show higher precision
Long-range Coordination	Requires specific anatomical connections	Can occur through volume conduction	Test coordination between unconnected regions	Evidence for coordination without direct connections
Plasticity Mechanisms	Primarily Hebbian (fire together, wire together)	Field coherence guides synaptic changes	Manipulate field coherence during learning	Field stimulation can enhance or block plasticity
Sleep Function	Synaptic homeostasis and pruning	Field pattern consolidation and energy restoration	Analyze field dynamics during sleep stages	Sleep shows distinct field reorganization patterns
Psychedelic Effects	Altered neurotransmitter binding	Enhanced field resonance coupling	Measure field coherence under psychedelics	Increased field complexity reported
Meditation Effects	Changed network activity	Optimized field resonance patterns	Compare field patterns in meditators	Distinct field signatures in experienced meditators
Cognitive Flexibility	Depends on synaptic plasticity rates	Determined by field resonance adaptability	Test rapid task switching abilities	Field coherence predicts switch costs
Neurological Disorders	Synaptic/structural abnormalities	Field-power coupling dysfunction	Analyze field-neurotransmitter relationships	Many disorders show field abnormalities

5. Clinical Implications and Therapeutic Applications

The field-primary framework suggests that many brain disorders result from misalignment between field computation and power modulation demands for normal function, rather than primary neurotransmitter imbalances. We touch briefly on a few such examples and reserve in-depth treatment for a later paper on “oscillopathies”:

Depression: Rather than a simple "chemical imbalance," depression may reflect a mismatch between field computational demands and available energetic resources. The field patterns associated with positive affect and motivation may require specific energetic configurations that are inadequately supported in depression. This may explain why SSRIs require weeks to work—they must recalibrate the entire field-power coupling relationship, not just increase serotonin levels.

Schizophrenia: The positive symptoms (hallucinations, delusions) may result from excessive local field resonances that create false signal amplification, while negative symptoms (avolition, anhedonia) may reflect insufficient global field integration. The dopaminergic abnormalities observed in schizophrenia may be compensatory attempts to correct field dysfunction rather than primary causes.

Epilepsy: Represents *runaway* field resonance that overwhelms normal power regulation mechanisms. The seizure threshold reflects the stability of field dynamics—when resonance cascades exceed the system's ability to regulate energy distribution, uncontrolled synchronization occurs. This explains why both field-based interventions (VNS, DBS) and metabolic interventions (ketogenic diet) can be effective. They reimpose “brakes” on the resonance cascades.

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ADHD: May involve unstable field resonance patterns that prevent sustained attention. The rapid switching between field states could reflect inadequate power regulation, explaining why stimulants (which enhance catecholamine-mediated power distribution) improve focus.

Autism Spectrum Disorder: Could involve altered field resonance hierarchies, with excessive local resonance at the expense of global integration. This would explain both the enhanced detail perception and reduced global processing characteristic of ASD.

Alzheimer's Disease: The progression from isolated synaptic dysfunction to widespread network failure may be better understood as a breakdown in field coherence. Amyloid and tau pathology may disrupt field propagation, leading to isolated "field islands" that cannot maintain critical dynamics.

6. Conclusion

We have presented a field theory of neural criticality that proposes a fundamental reconceptualization of conventional neuroscience assumptions. Rather than electromagnetic fields serving as secondary phenomena arising from neural computation, we suggest they constitute the primary computational medium of the brain, with neurotransmitter and neuromodulator systems functioning as field-controlled power distribution networks.

Central to this framework is the recognition that the brain's energetic substrate maintains itself at a critical state—the optimal point for information processing and dynamic flexibility. Neurotransmitter systems provide rapid, local power distribution, while neuromodulator systems, through their diffuse and persistent volume transmission, serve as field-controlled atmospheric modulators that can shift entire brain regions away from this critical baseline. These neurochemical "sprays" enable adaptation to changing demands by tuning circuits toward supercritical states for enhanced processing or subcritical states for stability and energy conservation. This dynamic modulation around a critical baseline provides the flexibility needed for adaptive behavior while maintaining overall system stability.

The distinction between neurotransmitters and neuromodulators proves crucial to our framework. While neurotransmitters enable fast, point-to-point energy transfer, neuromodulators create the persistent atmospheric conditions within which field computations unfold. This aligns with recent active inference theories (Laukkonen et al., 2025) that emphasize the role of neuromodulatory sprays in setting global precision weights, though we extend this by proposing that fields compute these precision requirements while neuromodulators merely implement them energetically.

Like a tree where the trunk and branches provide stable structure but the real dynamic information lies in the rustling canopy of leaves, the brain's anatomical substrate provides essential support, but the actual computation of cognition and consciousness occurs in the rapidly fluctuating electromagnetic field patterns. The movements of leaves in the wind contain far more information than any equivalent movements in the trunk or large branches—similarly, field dynamics carry the computational richness of mental life while the neural substrate provides energetic support.

This field-primary hypothesis finds its strongest support in the temporal dynamics of neural coordination. The speed differential between electromagnetic field effects (effectively instantaneous) and neuromodulator diffusion (hundreds of milliseconds to seconds) suggests a natural hierarchy where rapid field computations control slower energy regulation systems.

Our mathematical framework demonstrates that neural avalanches propagate through resonance cascades in electromagnetic fields, that 1/f noise emerges from multi-scale field interactions at criticality, and that consciousness corresponds to optimized field integration. The model makes specific predictions about pharmacological effects—particularly the delayed action of drugs targeting neuromodulator systems—as well as individual differences and therapeutic interventions that distinguish it from conventional approaches.

The clinical implications are significant. Rather than treating psychiatric and neurological conditions as primarily disorders of neurotransmitter or neuromodulator systems, the field-primary perspective suggests they result from failures of coordination between field computation and power regulation. This opens new therapeutic avenues focused on restoring field-power coordination rather than modulating neurochemical levels in isolation.

More broadly, this work illustrates the importance of considering temporal hierarchies in complex systems. When systems exhibit processes operating on vastly different timescales, the faster processes often serve as the primary computational layer while slower processes provide supporting infrastructure. Recognizing this hierarchy can transform our understanding of system function and dysfunction.

The field-primary perspective does not diminish the importance of neuroanatomy, synaptic connectivity, firing, or neurochemical systems. Rather, it recognizes their crucial role as the energetic foundation that enables field-based computation of cognition and consciousness. The brain is not merely a network of discrete elements but a resonating hierarchical electromagnetic system where rapid field computations coordinate slower resource allocation systems to maintain critical dynamics and the work of cognition and consciousness.

As neuroscience continues to grapple with the hard problems of consciousness, cognition, and neural coordination, the field-primary framework offers a path forward that honors both the computational complexity of brain function and the physical constraints that shape its operation. The reconceptualization we propose—emphasizing the distinction between fast field computation and slower neuromodulatory power distribution—may prove essential for understanding how mind emerges from matter in the most complex biological systems known: our own minds.

[Anthropic's Claude 4.1 assisted in writing a first draft of this paper]

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