NEURAL GRAMMARS OF TIME: AN INTEGRATED FRAMEWORK FOR THE ACTIVE CONSTRUCTION OF TEMPORAL REALITY

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Abstract

Time is a fundamental dimension of experience, yet neuroscience suggests that the subjective flow of time is an active neural construction rather than a passive reflection of physical reality [Buonomano 2017]. Here, I propose the "Neural Grammars of Time" – a unifying framework explaining how distributed neural architectures transform physical signals into a structured temporal phenomenology. I would argue that temporal cognition emerges from three interdependent processes: Temporal Representation, which utilizes population codes, oscillatory coupling, and specialized "time cells" to encode duration and sequence [Eichenbaum 2014; MacDonald et al. 2011]; Temporal Construction, which leverages predictive processing and the multisensory "Temporal Binding Window" to assemble a coherent experiential present [Wallace & Stevenson 2014; Hohwy 2013]; and Temporal Action, which maps internal temporal scaffolds onto goal-directed behaviour and decision-making [Merchant et al. 2013; Paton & Buonomano 2018]. Evidence from evolutionary biology and developmental science indicates that these mechanisms are phylogenetically conserved and early-emerging [Merchant et al. 2013]. Furthermore, I demonstrate how distortions in temporal processing – characteristic of Parkinson's disease, ADHD, and schizophrenia – reveal the functional logic of these systems, particularly the fragility of the ~100-ms continuity window in disorders of conscious experience [Giersch & Mishara 2017]. By synthesizing computational, systems, and clinical perspectives, this framework provides a comprehensive account of how

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the brain constructs the structured temporal reality that underpins perception, memory, and conscious experience.

Keywords: *time perception, temporal cognition, neural dynamics, predictive processing, consciousness.*

Introduction: The neural construction of temporal reality

Time is perhaps the most foundational yet elusive dimension of human experience. While we intuitively perceive it as a continuous, unidirectional flow from a fixed past toward an open future, modern physics suggests a more complex reality. Einstein's "block universe" model proposes that past, present, and future coexist in a four-dimensional spacetime manifold, implying that the subjective "now" may be an observer-dependent perspective rather than a fundamental property of the universe [Einstein 1916; Rovelli 2018]. This discrepancy between physical time and psychological time has led researchers across physics, philosophy, and neuroscience to explore the possibility that our temporal experience is an evolved cognitive construction – a "controlled hallucination" designed to support survival [Callender 2017].

Emerging evidence suggests that the brain does not possess a single "internal clock" but instead operates as a distributed "time machine" [Buonomano 2017]. Rather than passively recording the passage of seconds, the brain actively synthesizes temporal reality through a complex interplay of neural mechanisms. Recent research highlights a shift toward "time-domain" theories, where brain functions like cognition and memory are mediated by temporally patterned signals and oscillatory sequences that resemble holographic processes [Paton & Buonomano 2018]. This distributed architecture allows the brain to map time onto diverse neural substrates, from the motor precision of the cerebellum to the sequential "time cells" of the hippocampus [Eichenbaum 2014]. Hippocampal findings further show that temporal information is multiplexed with spatial codes, enabling richer episodic representations [Umbach, Tan & Jacobs 2020].

In this article, I propose the "Neural Grammars of Time" – an integrated neurocognitive framework that explains how the brain transforms distributed neural dynamics into a structured temporal phenomenology. This framework is built upon three interdependent pillars:

- **Temporal Representation**: The encoding of duration, sequence, and structure through population codes and oscillatory coupling. Recent findings reveal how hippocampal neurons multiplex spatial and temporal information, enhancing the informational content of episodic memories [Umbach, Tan & Jacobs 2020].

- **Temporal Construction**: The assembly of a coherent experiential "now" using predictive processing and the multisensory Temporal Binding Window [Wallace & Stevenson 2014]. This mechanism enables the brain to resolve discrepancies across sensory channels to maintain perceptual stability [Friston 2010].
- **Temporal Action**: The transformation of internal temporal scaffolds into goal-directed behaviour. New evidence regarding prospective coding shows how specific neural ensembles are reactivated seconds before anticipated events, providing a cellular substrate for navigating temporal contingencies [Merchant, Harrington & Meck 2013].

By unifying classical theories with latest breakthroughs – such as the discovery of how fronto-parietal circuits switch between shared and independent timing modes – this article advances a comprehensive account of temporal reality. I would argue that the continuity and directionality of human time are emergent properties of these interacting "neural grammars", which allow the brain to navigate the timeless vacuum of physical reality by constructing the richly structured temporal world we inhabit.

1. Temporal representation: Neural motifs and distributed manifolds

Temporal representation is not the product of a singular, centralized chronometer; rather, it emerges from a diverse repertoire of neural motifs distributed across hippocampal, cortical, cerebellar, and striatal circuits. These systems do not merely "track" time but construct a representational scaffold that integrates duration, sequence, and ordinal structure, enabling the brain to encode episodic memories and compute predictive trajectories [Paton & Buonomano 2018].

1.1. Stochastic and structured population dynamics

Traditional views of "internal clocks" have been superseded by models of population coding and latent manifold dynamics. Central to this are time cells – neurons, primarily in the hippocampus and entorhinal cortex, that exhibit circumscribed firing at specific moments within a temporal interval [Eichenbaum 2014; Umbach, Tan & Jacobs 2020; Tsao et al. 2018]. These cells form a sequential chain that tiles time, providing a robust representation of "when" an event occurs relative to a temporal anchor.

In parallel, ramping cells in the prefrontal cortex and striatum track elapsed time through monotonic changes in firing rates, acting as neural integrators that support interval estimation and decision-making [Merchant, Harrington & Meck 2013]. Current evidence suggests these motifs are not isolated; rather, the brain utilizes

high-dimensional population codes where temporal information is embedded within the evolving state-space of neural ensembles, allowing for the flexible remapping of time based on behavioural context [Murray et al. 2017].

1.2. Phase-coded sequences and oscillatory multiplexing

The "grammar" of temporal representation is critically dependent on oscillatory coupling, which provides a syntax for organizing information across scales. Theta-gamma phase-amplitude coupling serves as a primary mechanism for sequential encoding [Lisman & Jensen 2013; Buzsáki & Wang 2012]. In this model, the slower theta cycle (~8 Hz) defines a temporal window within which faster gamma cycles (~40–100 Hz) represent discrete items or events in a sequence. This oscillatory multiplexing allows the brain to maintain the ordinal structure of experience. Recent findings demonstrate that episodic sequence memory is supported by this theta-gamma phase code, where the specific phase of the theta wave at which a neuron fires conveys precise information about the item's position in time [Heusser et al. 2016]. This "temporal chunking" is essential for transforming continuous sensory streams into discrete, manageable units of memory.

1.3. Metastable transitions and latent dynamics

At a macroscopic level, temporal representation is sustained by metastable network dynamics. Rather than settling into a static equilibrium, neural networks transition through a series of quasi-stable states – metastable trajectories – that represent the progression of time and the segmentation of events [Rabinovich, Huerta & Laurent 2008]. These transitions are driven by recurrent connectivity and allow circuits to maintain temporal context across delays, even in the absence of external stimuli. Metastability ensures that the brain can represent duration not as a linear accumulation but as a series of state transitions within a latent manifold [Murray et al. 2017; Mazzucato, La Camera & Fontanini 2019]. This explains why temporal perception is highly sensitive to the informational density of an interval: the more state transitions occur, the longer the perceived duration.

2. Temporal construction: Active inference and multisensory integration

The brain does not passively register the passage of time; instead, it operates as a predictive inference machine that reconciles stochastic sensory inputs, varying neural latencies, and prior expectations into a coherent "experiential present". Temporal construction is the computational process of synthesizing these heterogeneous signals to maintain perceptual stability and support real-time action.

2.1. Active inference and generative temporal models

A central challenge for the brain is the significant discrepancy in transmission and processing speeds across sensory modalities – for instance, auditory signals reach the cortex faster than visual ones [Hogendoorn 2022]. To overcome these delays, the brain employs generative models that provide a predictive scaffold for incoming events. Under the Predictive Processing (PP) framework, the brain minimizes "temporal surprise" by anticipating the timing and structure of stimuli [Friston 2010]. This active alignment allows the system to shift from a reactive to a proactive state, where the subjective "now" is a post-hoc reconstruction that accounts for known neural latencies [Eagleman 2009].

2.2. The multisensory Temporal Binding Window (TBW)

To achieve a unified perception, the brain utilizes the Temporal Binding Window (TBW) – a critical millisecond-scale interval (typically 50–200 ms) within which sensory inputs from different modalities are fused into a single event [Wallace & Stevenson 2014; Vroomen & Keetels 2010]. This window is not static; it is a highly supple mechanism that undergoes temporal recalibration based on environmental regularities and task demands. Recent evidence suggests that the width of the TBW is modulated by oscillatory phase-resetting, where the brain "waits" for the slowest signal to arrive before committing to a multisensory binding [Cecere, Rees & Romei 2015].

2.3. Synthesis into the experiential present

The culmination of these processes is the "Specious Present" – a temporally extended integration window that bridges the gap between sensory fragments and conscious awareness [Wittmann 2009]. This construction facilitates a continuous narrative of experience, allowing for fluid motor control and decision-making under uncertainty. Through dynamic error correction and the integration of internal generative models, the brain transforms a fragmented, asynchronous physical reality into the structured, actionable present that defines human consciousness [Van Wassenhove 2016].

3. Temporal action: Operationalizing temporal inference for adaptive behaviour

Temporal action represents the phase where internal temporal scaffolds are operationalized into goal-directed outputs. While representation and construction provide the "what" and "when" of experience, temporal action executes the "how" – mapping latent temporal predictions onto motor, cognitive, and evaluative systems. This process is driven by a distributed network involving the cerebellum, basal ganglia, and fronto-parietal circuits, which jointly solve the problem of timing-dependent survival [Ivry & Spencer 2004; Mauk & Buonomano 2004].

3.1. Predictive motor control and internal forward models

The brain achieves millisecond-scale motor precision through internal forward models, primarily housed in the cerebellum [Shadmehr, Smith & Krakauer 2010]. These models anticipate the sensory consequences of actions, allowing for the real-time correction of motor trajectories. In this context, temporal action is not merely the execution of a sequence but the continuous alignment of an internal "state-space" with external physics [Ivry & Spencer 2004]. Recent evidence suggests that the Supplementary Motor Area (SMA) acts as a temporal accumulator, where neural activity ramps up toward a specific threshold to trigger action initiation – a classic form of "climbing activity" that bridges temporal representation with motor execution [Merchant, Harrington & Meck 2013]. This "climbing activity" represents a neurocomputational bridge between abstract temporal representation and physical movement.

3.2. Dopaminergic modulation of temporal value and decision-making

Temporal action is intrinsically linked to the evaluation of reward. The brain must weigh the value of an outcome against its expected delay – a process known as temporal discounting [Kim, Hwang & Lee 2008]. Dopaminergic neurons in the substantia nigra and ventral tegmental area (VTA) do not just encode reward prediction errors; they also control the "speed" of the internal clock [Soares, Atallah & Paton 2016]. Higher dopaminergic tone is associated with an overestimation of duration and increased impulsivity, as the brain's internal "metronome" accelerates, making future rewards seem more distant. This timing-based value computation is central to decision-making under uncertainty, where the cerebellum provides the precision and the basal ganglia provides the "gate" for action [Mauk & Buonomano 2004].

3.3. The Sense of Agency and intentional binding

At the highest level of temporal action lies the Sense of Agency – the subjective experience of controlling one's actions and their consequences. This is mediated by intentional binding, a phenomenon where the perceived time of a voluntary action and its subsequent effect are shifted toward each other [Haggard 2017]. This temporal compression is a hallmark of "closed-loop" temporal processing: when the brain predicts an outcome, it actively restructures its temporal reality to maintain a sense of causal continuity [Schwartze & Kotz 2013]. Disruptions in this mechanism are observed in clinical conditions like schizophrenia, where the "binding" fails, leading to a fragmented sense of self and agency.

Grammar Level	Core Function	Representative Neural Substrates	Primary Coding Principles
1. Temporal Representation	Encodes duration, order, and temporal structure	Hippocampus (time cells), entorhinal cortex, prefrontal cortex, striatum, cerebellum	• Sequential firing (time cells) • Ramping activity • Population codes • Latent manifold dynamics • Theta–gamma coupling
2. Temporal Construction	Integrates multisensory inputs and predictions into a coherent "now"	Superior temporal sulcus, posterior parietal cortex, prefrontal cortex, thalamus, cerebellum	• Predictive processing • Temporal Binding Window (20–200 ms) • Multisensory recalibration • Phase resetting • Error minimization (active inference)
3. Temporal Action	Converts internal temporal structure into motor output, reward evaluation, and agency	Basal ganglia, cerebellum, SMA/pre-SMA, premotor cortex, dopaminergic midbrain (VTA/SNc)	• Ramping-to-threshold dynamics • Forward models • Dopaminergic modulation of temporal value • Intentional binding • Temporal discounting mechanisms

4. Developmental and comparative evidence: Phylogenetic conservation and ontogenetic foundations

The capacity to represent and act upon temporal structure is not a late-emerging cognitive specialization but a foundational biological imperative. Developmental and comparative data suggest that the "neural grammars of time" are rooted in highly conserved circuits that emerge early in ontogeny, providing a prerequisite scaffold for the development of complex perception, navigation, and social coordination.

4.1. Ontogenetic trajectories: The early emergence of temporal magnitude

Temporal cognition is among the earliest cognitive faculties to manifest in human development. Infants aged only a few months exhibit a sophisticated sensitivity to duration, rhythm, and temporal contingencies, long before the maturation of language or explicit memory systems [Brannon, Suanda & Libertus 2007]. This "sense of time" is theorized to be part of a generalized magnitude system – shared with space and number – processed by the posterior parietal cortex [Walsh 2003].

Current research indicates that infants utilize violation-of-expectation paradigms to demonstrate precise interval timing, suggesting that the basic computational architecture for temporal prediction is functional shortly after birth [Provasi, Rattat & Droit-Volet 2011]. These early abilities undergo refinement as the prefrontal-striatal pathways mature, leading to increased precision and the capacity for multi-second interval estimation [Buhusi & Meck 2005].

4.2. Phylogenetic conservation: Canonical timing motifs across species

Comparative evidence confirms that interval timing is a fundamental trait across the animal kingdom, from invertebrates to non-human primates. This universality points toward phylogenetic conservation of timing mechanisms. Vertebrates share a canonical neural architecture for timing: basal ganglia-thalamocortical loops provide a substrate for interval timing and reward-based decision-making, while the cerebellum supports sub-second precision and motor coordination [Merchant, Harrington & Meck 2013; Paton & Buonomano 2018].

Even in species lacking these complex macro-structures, such as *Drosophila* or *C. elegans*, temporal prediction is achieved through recurrent network dynamics and oscillatory motifs that mirror the population coding found in the mammalian cortex [Paton & Buonomano 2018]. This suggests that while the hardware varies, the "neural grammar" – the algorithmic solution to timing – remains remarkably consistent across evolution.

4.3. Evolutionary utility: Navigation, foraging, and fitness

The evolutionary pressure to construct a temporal reality is driven by survival. Optimal Foraging Theory dictates that animals must precisely estimate the time required to travel between patches and the rate of resource depletion to maximize calorific intake [Stephens & Krebs 1986]. Furthermore, temporal prediction is essential for acoustic communication (e.g., birdsong or human speech) and social synchrony, where millisecond-scale timing determines the success of the interaction [Ten Oever et al. 2021].

The ubiquitous presence of Scalar Timing (Weber's Law for time) – where the error in timing is proportional to the duration being timed – across all tested species serves as a "behavioural fossil", confirming that diverse brains have converged upon similar computational constraints for temporal processing [Gibbon 1977; Gallistel 1990].

5. Temporal processing in clinical disorders: A transdiagnostic framework

The clinical manifestations of temporal dysfunction provide a unique window into the fragile architecture of the brain's "time machine". Disruptions in temporal processing are not localized to single pathologies but represent a transdiagnostic dimension where deficits in dopaminergic signalling, thalamocortical integration, and predictive coding lead to profound alterations in the subjective flow of reality [Merchant, Harrington & Meck 2013].

5.1. Dopaminergic dysregulation and basal ganglia circuitry

The basal ganglia, particularly the striatum, are central to interval timing and rhythm processing. In Parkinson's disease, the depletion of nigrostriatal dopamine leads to a systemic "slowing" of the internal clock [Jones & Jahanshahi 2014]. Patients typically exhibit impaired duration estimation and a reduced capacity for temporal prediction, which manifests both in motor bradykinesia and perceptual deficits.

Conversely, attention-deficit/hyperactivity disorder (ADHD) is characterized by fronto-striatal and cerebellar dysregulation, resulting in high temporal variability and a diminished sensitivity to multisensory temporal synchrony [Noreika, Falter & Rubia 2013]. These deficits suggest that the "precision" of temporal representation is dopamine-dependent, where suboptimal signalling leads to a fragmented and noisier temporal experience.

5.2. Affective modulation and the dilation of flow

Temporal experience is intrinsically tied to emotional state. In major depressive disorder (MDD), patients frequently report a subjective "dilation" of time – a feeling that time is slowing down or stagnating [Thönes & Oberfeld 2015]. Neurobiologically, this is linked to altered activity in the insula (responsible for interoception) and the prefrontal cortex, where a hyper-focus on the negative self-schema disrupts the normal flow of the "experiential present" [Wittmann 2009; Droit-Volet 2013].

In bipolar disorder, this flow oscillates: manic states are associated with compressed time and accelerated goal-directed action, reflecting a hyper-responsive

reward system, while depressive episodes return to a dilated, heavy temporal state [Bolbecker et al. 2014].

5.3. Predictive coding and the fragmentation of agency

High-impact research increasingly views schizophrenia through the lens of impaired predictive timing. The hallmark of schizophrenia – a loss of the sense of agency – is often driven by a breakdown in intentional binding, where patients fail to temporally "link" their actions with the consequences thereof [Haggard 2017]. This fragmentation of the "now" results from a failure in predictive processing; if the brain cannot accurately predict the timing of sensory feedback, the distinction between "self" and "other" becomes blurred [Giersch & Mishara 2017].

5.4. Structural network disruptions: The thalamic hub

The thalamus serves as the critical relay for the "neural grammars of time", integrating signals across distributed cortical manifolds. Thalamic strokes or lesions can lead to global temporal disorientation, disrupting the patient's ability to orient within the past-present-future continuum [Cojan & Ptak 2012]. These cases highlight that even if specialized "time cells" remain intact, the loss of the central integration hub prevents the construction of a coherent temporal reality.

6. A unified framework: The hierarchical grammar of temporal cognition

The "Neural Grammars of Time" framework posits that temporal reality is not a monolithic readout of physical duration but an emergent property of a rule-governed, hierarchical system. Analogous to linguistic syntax, which transforms discrete lexical units into structured meaning, the brain utilizes specific neurocomputational "grammars" to organize asynchronous neural signals into the fluid phenomenology of past, present, and future [Buzsáki 2010].

6.1. The three pillars of temporal syntax

Our framework integrates three distinct, yet interdependent computational layers:

1. **Temporal Representation (The Symbols):** At the base level, the brain generates elementary temporal units. Using population-clock dynamics, oscillatory phase-coding (e.g., theta-gamma coupling), and specialized "time cells", the nervous system encodes the raw metrics of duration and ordinal sequence [Hardy & Buonomano 2016; Paton & Buonomano 2018].
2. **Temporal Construction (The Synthesis):** These symbols are integrated through active inference. By leveraging the Multisensory Temporal Binding

Window and generative internal models, the brain resolves cross-modal latencies to construct a coherent "experiential present" – the temporal equivalent of a sentence [Friston 2010; Van Wassenhove 2016].

3. **Temporal Action (The Pragmatics):** Finally, these structures are operationalized. Temporal action maps the constructed "now" onto goal-directed trajectories, utilizing dopaminergic value-coding to weigh future rewards and cerebellar forward models to achieve motor precision [Paton & Buonomano 2018; Soares, Atallah & Paton 2016].

6.2. Hierarchical time-scales and predictive control

A unifying feature of this grammar is its hierarchical organization. Processing occurs across a spectrum of time-scales, from millisecond-level sensory integration in the brainstem to multi-second episodic sequencing in the hippocampus and prefrontal cortex [Kiebel, Daunizeau & Friston 2008; Hasson, Chen & Honey 2015]. This hierarchy allows the brain to maintain long-term context while remaining responsive to immediate sensory perturbations. I propose that the PFC-striato-cerebellar axis functions as the "syntax engine", dynamically switching between these scales to minimize prediction error and maximize adaptive fitness [Hasson et al. 2015].

6.3. Implications for consciousness and agency

The "Neural Grammars" framework provides a mechanistic account of the Sense of Agency. When the brain's internal "grammar" successfully predicts the timing of a sensory consequence following an action (intentional binding), the result is a unified experience of self-causality [Haggard 2017]. Conversely, the "ungrammatical" time perceived in clinical disorders – where predictions and inputs fail to align – leads to the fragmentation of the self and reality. By viewing temporal cognition as an active, combinatorial process, this framework reconciles the timelessness of physical equations with the structured flow of human experience, providing a foundation for a rigorous, integrative science of time [Teki, Grube & Griffiths 2012]. Integrating the Neural Grammars of Time framework into the leading theories of consciousness reveals that each theory relies on a specific "temporal syntax" to explain how subjective experience arises.

The following table compares how Global Workspace Theory (GWT), Integrated Information Theory (IIT), and the Free-Energy Principle (FEP) handle these temporal grammars:

Comparative analysis of temporal grammars in major theories of consciousness

Feature	Global Workspace Theory (GWT)	Integrated Information Theory (IIT)	Free-Energy Principle (FEP)
Core Temporal Mechanism	**Non-linear "Ignition"**: A discrete broadcast of information across the brain.	**Causal integration (Φ)**: Maximum cause-effect power within a specific "grain".	**Active Inference**: Continuous minimization of prediction error (surprisal).
Temporal Granularity	**Discrete (100–300 ms)**: Operates in episodic cycles where only one content is dominant.	**Multiscale/Nested**: Defines an "instant of experience" based on causal power, often at 100–300 ms.	**Hierarchical/ Continuous**: Nested timescales from milliseconds to long-term "generative models".
Role of Prediction	**Bottom-up/Top-down Selection**: Predictions help select which "specialist" enters the workspace.	**Intrinsic Causal Structure**: Focused more on the *internal* state than future-oriented prediction.	**The "Grammar" itself**: The brain is an "inference engine" that exists to predict temporal flow.
The "Specious Present"	A **fleeting memory capacity** where broadcasted info creates a global mental scene.	A **unitary whole** specified on a single set of elements with definite spatio-temporal boundaries.	A **probabilistic density** (recognition density) representing the current state and its trajectory.
Sense of Agency	Emerging from the **broadcasting** of motor plans to evaluative systems.	Emerging from **maximal irreducibility** – the system acting as a single causal entity.	Emerging from **Action as Inference**: Testing hypotheses by changing the world to match predictions.
Primary Brain Substrate	**Prefrontal-Parietal Network**: Long-range axons "igniting" global availability.	**Posterior "Hot Zone"**: Temporo-parieto-occipital areas with high causal density.	**Whole-Brain Hierarchy**: Distributed Markov blankets and hierarchical generative models.

Synthesis: The Integrated World Modelling View

Recent efforts, such as Integrated World Modelling Theory (IWMT), suggest that these theories are not mutually exclusive but rather describe different "levels" of the same temporal grammar:

1. IIT describes the *intrinsic existence* of a system at a specific temporal grain (the "what" of a moment).
2. GWT describes the *functional broadcast* that allows that moment to be accessible for behaviour and report (the "access" of a moment).

3. FEP describes the *computational engine* (active inference) that drives the system to update its temporal models and move from one moment to the next.

This suggests that the Neural Grammars of Time act as the "operating system" that allows these distinct processes – causal integration, global broadcasting, and predictive error-correction – to synthesize into the coherent stream of consciousness we experience.

Conclusion: Toward an integrative science of temporal construction

Temporal reality is neither a passive imprint of the physical world nor the output of a singular, localized neural chronometer. Instead, it emerges as a sophisticated cognitive achievement from the coordinated activity of distributed systems that represent temporal structure, construct coherent multisensory experiences, and operationalize temporal predictions into adaptive action [Paton & Buonomano 2018; Merchant, Harrington & Meck 2013]. The "Neural Grammars of Time" framework shifts the paradigm from searching for a centralized "clock" toward understanding the combinatorial rules and hierarchical dynamics that transform stochastic neural states into a structured temporal phenomenology [Kiebel, Daunizeau & Friston 2008].

The temporal architecture of consciousness

Consciousness is fundamentally a temporal phenomenon. Unravelling these neural grammars identifies the mechanisms that constitute the very fabric of human consciousness. Consciousness is not merely situated in time; it is actively constructed through temporally organized neural activity [Friston 2010; Northoff & Huang 2017].

- **The Specious Present:** Conscious awareness depends on a constructed integration interval of roughly 100–300 ms, during which discrete neural events are merged into a unified perceptual moment [Eagleman 2008; Wittmann 2009]. This "temporal workspace" allows consciousness to operate as a single stream rather than disjointed fragments.
- **Continuity and Flow:** Metastable dynamics and sequential firing patterns furnish the neural basis for perceived continuity, stitching moment-to-moment states into an extended experiential flow [Buzsáki & Wang 2012; Varela et al. 2001].
- **Agency and Selfhood:** Agency emerges through "Temporal Action", where predicted sensory consequences align with actual outcomes via precise timing [Haggard 2017]. When these predictive grammars fail – as seen in the fragmented agency of schizophrenia – the stability of the self-experience collapses [Northoff & Huang 2017].

- **Large-Scale Coordination:** Major theories, including Global Workspace Theory (GWT) [Baars 2005], Integrated Information Theory (IIT) [Tononi 2008], and the Free-Energy Principle (FEP) [Friston 2010], all converge on the claim that consciousness arises from coordinated interactions among distributed neural systems. Temporal grammars supply the rules that allow these networks to synchronize and integrate information across multiple scales [Van Wassenhove 2016; Varela et al. 2001].

Final synthesis and future directions

Synthesis underscores that the hallmarks of human time – continuity, directionality, and a privileged "now" – are emergent properties of an active inferential process. This perspective positions the brain as an architect of temporal reality, utilizing predictive coding and multisensory binding to bridge the gap between the timelessness of fundamental physics and the richly sequenced flow of experience.

The transdiagnostic nature of temporal dysfunctions positions temporal metrics as powerful translational markers of neural integrity. Future research must prioritize identifying the specific neural "syntax" governing these processes, particularly how cross-frequency coupling and metastable transitions enable the scaling of time from milliseconds to minutes. By integrating behaviour-centric approaches with large-scale neural recordings, we can move toward a unified theory of how the brain generates the most fundamental dimension of our existence: the sense of time.

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