

Neural Mechanisms of Temporal Perception

A Function First Approach to Operationalizing Time Consciousness

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Abstract & Objectives

Time consciousness is a fundamental aspect of experience. However, it remains a poorly understood phenomenon due at least in part to conceptual ambiguities and limited empirical data. This research aims to help address these challenges by examining the neurocomputational foundations of temporal perception through two models. These models focus on the computational tasks performed by neural ensembles, allowing us to subsequently extrapolate their functions in the larger cognitive system from a principled stand-point.

Abstract

This study analyzes striatal duration discrimination mechanisms in mice and proposes a similar mechanism in the human basal ganglia, with a key distinction in propagational behavior. This distinction may explain key features of time consciousness when combined with existing neuroscientific mechanisms and theoretical constructs. The function-first approach focuses on actual computational functions, aligning theoretical discussions with empirical data. It suggests that time consciousness is not about time itself but about estimating "the amount of things happening at this given moment," the rate of events. I argue that what we phenomenally perceive as the rate of time's passage is instead the brain's way of calculating, accommodating, and responding to, the amount of things happening in the mental environment.

Objectives

This study aims to address gaps in the literature on time consciousness, specifically those highlighted by Kent & Wittmann¹. As such, here I have used the goals outlined by them as my objectives. The primary objective overall is to explore and elucidate the neural mechanisms possibly underlying time consciousness. The study aims to help bridge the gap between empirical neuroscience and the phenomenological experiences of time by introducing a model that explains how the brain could process the experience of time from milliseconds to seconds. Specifically, the research aims to explain:

1. The subjective feeling of a continuous flow of time.
2. The variability in the perception of the flow of time & rate of its passage.
3. The duration of the experienced moment.
4. How the perception of time's passage affects thought and action.
5. How these perceptions, thoughts, and actions subsequently inform the subjective feeling of time.

This study attempts to integrate our understanding of neurological function with subjective experiences of time's flow, aiming to provide a framework that connects biological processes with individual perceptions. This model is a dedicated population clock model (see Paton & Buonomano²).

Background

Numerous time-telling mechanisms have been identified in the brain. However, a significant challenge in understanding these mechanisms is the lack of conclusive evidence showing that a specific time-telling area calculates time itself rather than reflecting another time process occurring elsewhere³. It is established that duration determinations can be derived from striatal activity⁴. However, it was not evident until recently that striatal activity directly determined these duration estimations. Temperature manipulations of the striatum in rats have shown that striatal population activity can dictate duration determination based decisions independent of motor control. Cooling the striatum slowed neural activity and timing judgments, while warming it sped them up, mimicking natural decision-related variability. These manipulations did not affect motor systems, indicating a specific role of striatal dynamics in decision timing³. Outside of experimental manipulations there are two primary modulators which can affect the speed at which a propagation flows through the striatal time ensemble. Dopamine from the substantia nigra (SN) can speed up or slow down signal propagation in the striatum⁵, as can ambient excitation driven by global activation⁶.

The BG are important to the study of consciousness due to their role in time-related processes, integration of signals from primary sensory areas, and because they are highly innervated by higher-order cortical areas. The BG also innervates the thalamus and hippocampus, which subsequently innervate the cortex at large. Given the importance of the BG in determining time duration and the emerging consensus of its importance in consciousness⁷, it is plausible that the BG is involved in time consciousness. The question then arises: if it is involved, how is it involved, and what is it doing?

Given the difficulties in defining time consciousness operationally, we might consider an alternative perspective. If focus on the functions being performed by the relevant neural systems, we find it likely that time consciousness is a product of the amount of activity occurring at a given time. That time consciousness is not a persistently faulty clock, but is instead a process keeping us abreast of the rate of events occurring.

Explanation of Model & Figure Relevance

Mouse Striatal Model: Demonstrates the population code executed by the striatal mouse circuit over time. Neurons activate sequentially, sending signals that correspond with elapsed time. Dopamine, serotonin, and ambient neural excitation influence the speed of the propagational wave.

Purpose: Establishes a neural basis for temporal perception by showing how striatal activity directly affects timing judgments. This model serves as the empirical foundation for proposing similar mechanisms in humans.

Proposed Basal Ganglia Model: Shows signal progression through the network in response to global cortical activation levels. The input signal starts weak, activates neurons with lower firing thresholds, strengthens, activates higher threshold neurons, and generally reflects the state of cortical activation.

Purpose: Suggests that the basal ganglia may code for the amount of activity occurring at a given time rather than time itself. This model supports the idea that time consciousness is about estimating the "amount of things happening at this given moment."

Continuity and Flow of Mental Content: Illustrates how the potentiation and activation of neural ensembles account for the continuity of mental percepts. Dynamic binding of neural ensembles allows for smooth transitions between thoughts.

Purpose: Explains the subjective feeling of a continuous flow of time and the duration of the experienced moment. This model addresses how overlapping activations create the perception of continuous mental content flow.

Proposed Neural Circuit: Integrates processes within the cortex, basal ganglia, thalamus, and hippocampus. The basal ganglia process the amount of cortical activity, influencing the thalamus and hippocampus, which then modulate cortical processes.

Purpose: Shows how the brain's estimation of event rates influences time consciousness. Dopaminergic inputs modulate these estimations, affecting the perceived rate of time's passage. This model ties together the empirical and theoretical aspects discussed in the previous sections.

Mouse Striatal Model

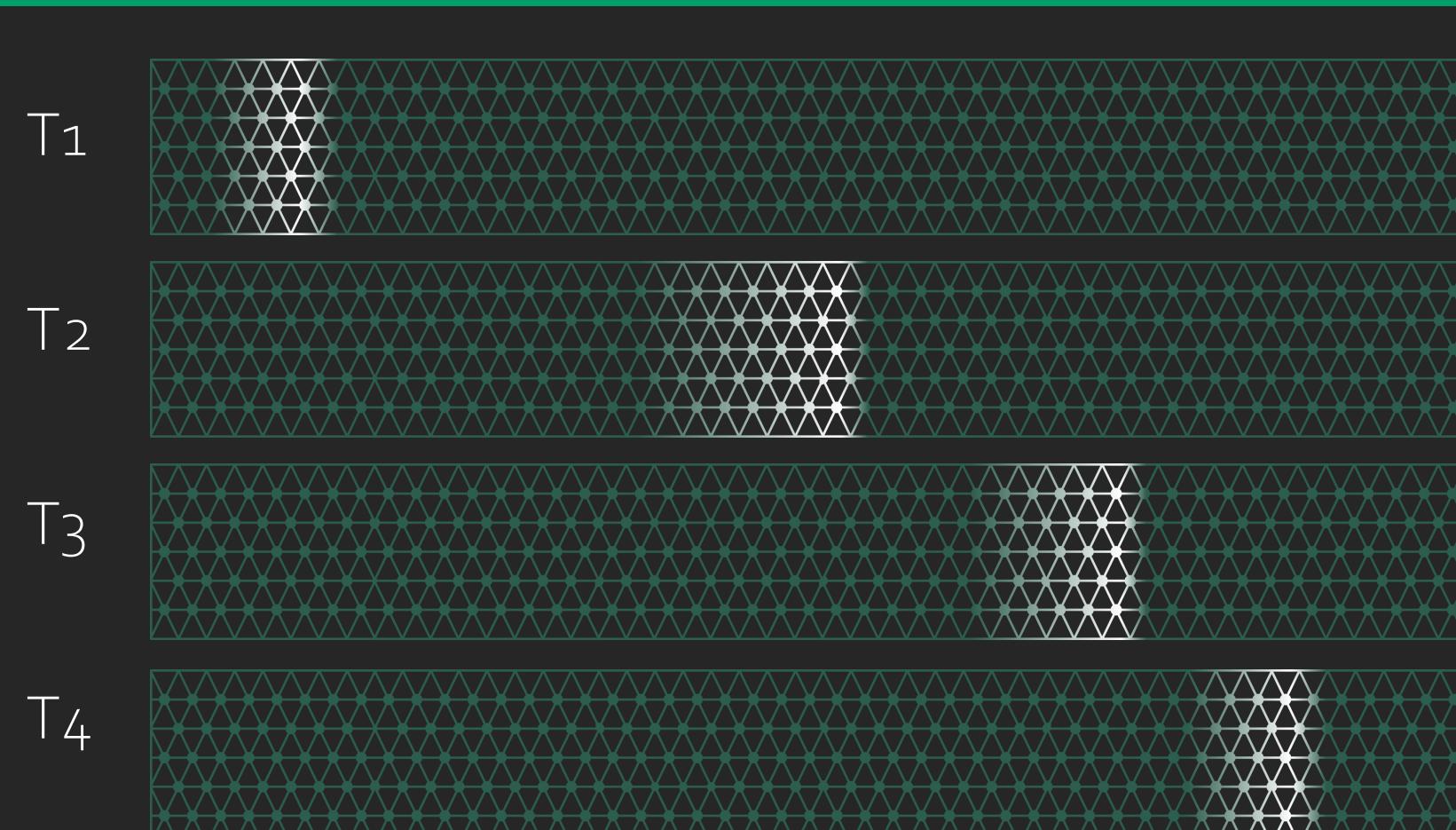


Figure 1: A Visualization of the Striatal Section of the Mouse Duration Evaluation Circuit

The progression from T0 to T4 demonstrates the population code executed by the striatal mouse circuit over time. When the neurons in dark green become active (white) they send out a signal through afferent projections which is subsequently turned into a duration evaluation. If the wave of propagation is mostly to the left, then the elapsed time is not much, if it is near the right, then more time has passed. Consequently, manipulations which alter the speed of the propagational wave lead to changes in evaluated time. Dopamine, serotonin, and ambient neural excitation all affect the speed of the propagational wave.

Visualization adapted from findings and data in Gouvea et. al. 3

Proposed Basal Ganglia Model

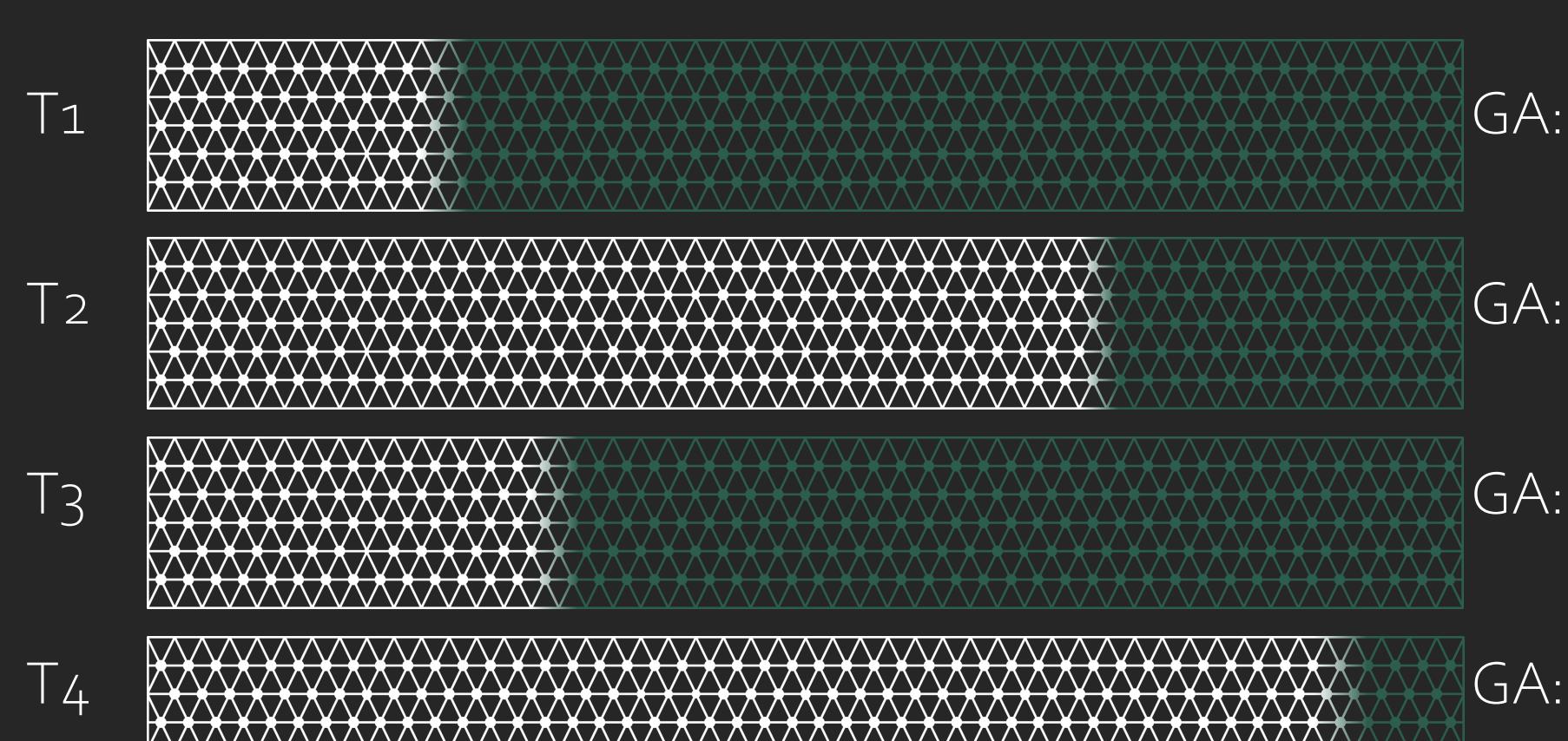


Figure 2: A Visualization of the Proposed Basal Ganglia Temporal Activity Integration Network

The progression from T1 to T4 shows the progression of the signal through time as the network corresponds to the afferent input strength or rather global cortical activation level (GA). The GA signal starts off weak, activating just the neurons with a lower firing threshold, and subsequently the signal strengthens at which point the neurons with higher firing thresholds become active. As the input signal weakens, the activation of the neurons in the network responds accordingly, and the formerly active higher threshold neurons stop being active. The mechanism can best be imagined as a sort of indicator akin to the gauge on a leaky pressure system, with the number of cortical cognitive events replacing the variable flow of gas. The process being undertaken here is the aggregation of activity within a variable timeframe. When there is little cortical activity, the circuit aggregates little activity. When there is a lot, it aggregates a lot, and this is reflected & processed through the activation of spatially organized neurons. So the downstream neural systems know when neuron X on the left and Y on the right are activated, there is a lot of activity, and when only x is active, there isn't.

Continuity and Flow of Mental Content

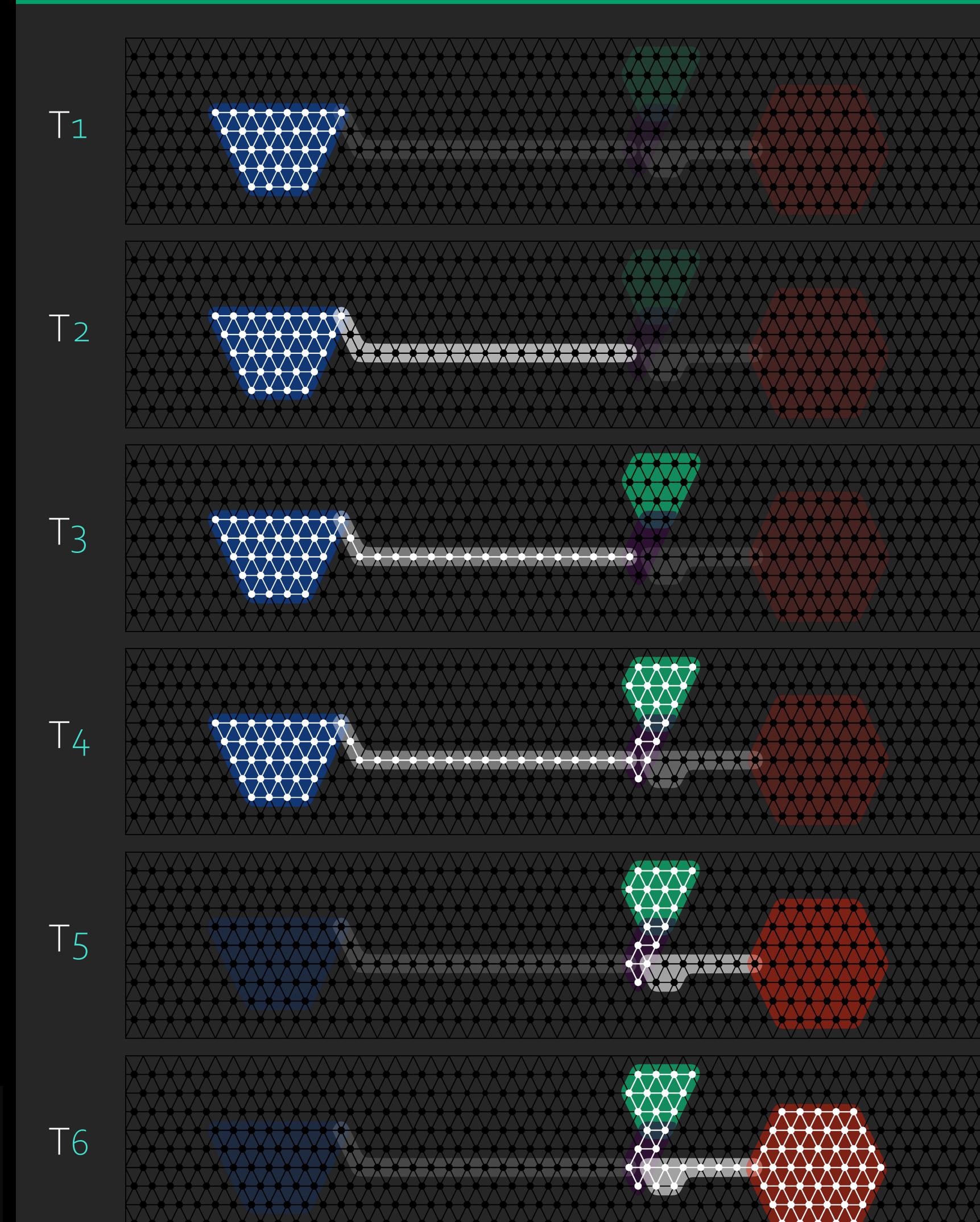


Figure 3: A Visualization of an Evolving Propagation in the Cortex

The progression from T1 to T6 visualizes how the potentiation and activation of neural ensembles could account for the continuity of mental percepts as in the example below. The colors surround a discrete set of neurons forming the ensemble for a particular mental object. In blue is the blueberry ensemble, in orange is the orange ensemble, in purple is the stem ensemble, and in green is the leaf ensemble. The strength of the color corresponds to the degree of potentiation. Inactive neurons are in black, & active ones in white. At T1 the blueberry ensemble is active, which potentiates the intermediary ensemble in white at T2. At T3 the potentiated intermediary ensemble fires, which potentiates the purple stem and closely related green leaf ensembles. At T4 the blueberry, stem, and leaf ensembles are activated. At T5, neural fatigue leads the blueberry ensemble to cease activating, and so the propagation in the leaf and stem ensembles continue to propagate, eventually coming to activate the orange ensemble fully, alongside the stem and leaf ensembles, at T6.

Example of Flow of Mental Contents

Imagine you're walking through an orange orchard. You get to your car and start thinking about blueberries, which you prefer. Imagining a blueberry, you think about how you've never seen a stem on it, and imagine a blueberry with a stem. Subsequently, you imagine an orange with a stem.

Processes Possibly Underlying Said Flow

A blueberry and a stem, two things normally not associated, come to fire and be processed as one through obligate reciprocal activation. This is facilitated by intermediary neural ensembles that help pass the signal between them. These intermediaries function by lowering the amount of activation necessary to pass a signal between two ensembles.

If binding is accomplished through this functional co-activation, then the mental objects being processed in the cortex would not abruptly appear and disappear from perception, but would rather evolve through intermediaries and fragments of mental objects, making a continuous dynamic and a subsequent perception of a contiguous train of thought.

This example illustrates how the dynamic binding of neural ensembles could lead to the fluid transition of processing or attention between mental objects over time.

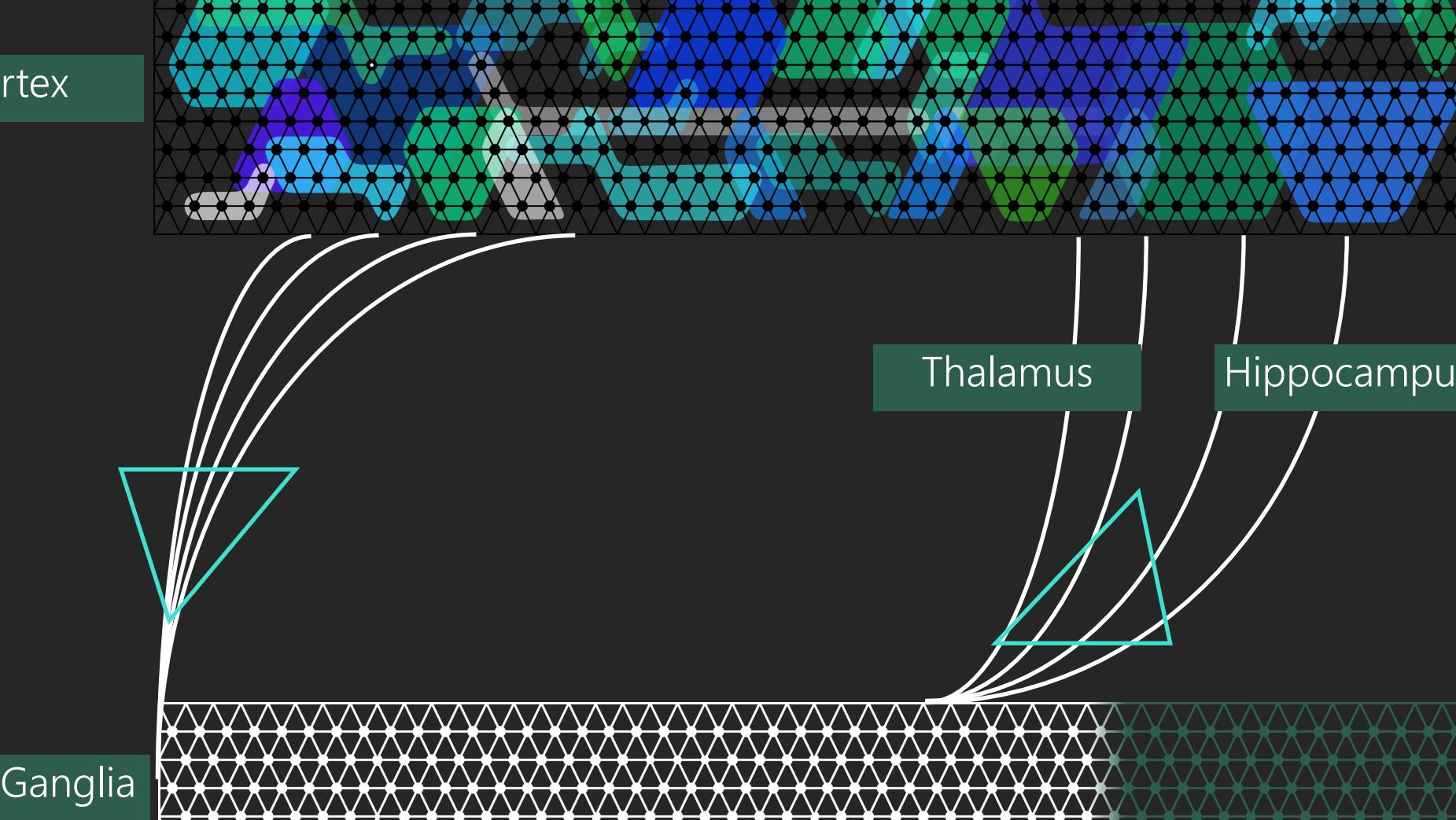
Proposed Cortex-Basal Ganglia-Thalamus x Hippocampus-Cortex Neural Circuit

Figure 4: An Illustration of the Entire Proposed Neural Circuit W/ All Relevant Mechanisms*

(*Substantia Nigra omitted for space. Arrows in teal point in the direction of system receiving input)

This model presents a conjectured circuit where the cortex provides inputs to the basal ganglia, which are then processed into a measure of cortical activation. The basal ganglia in turn communicates the measured degree of activation to the thalamus and hippocampus, which then allows the thalamus and hippocampus to modulate the dynamics of the cortex and other systems accordingly to suit the amount of activation reported by the basal ganglia, which is a proxy for the rate of events occurring. This modulation of the cortex then further informs the BG.

I conjecture that the hippocampus and thalamus integrate the signal to activate other ensembles active when the same degree of activation occurred. So when there is a lot of measured cortical activity, the hippocampus biases the cortex based on past experiences with high activity levels, to induce the dynamics which were previously employed in the high activity context. Meanwhile the thalamus ensures coordinated responses across the brain and similarly communicates or interprets the high activity to other neural systems.



Conclusion & Discussion

There is a plausible account of phenomenal time variability mediated by the substantia nigra, which through dopaminergic effects could extend the propagation through the basal ganglia system further than it would otherwise, with increased dopamine input leading to higher estimations of activity levels. This model provides a possible mechanistic substantiation of the idea that dopamine and positive experiences speed up the estimation of the rate of time's passage, further suggesting that time consciousness is more about determining and responding to the rate and type of events occurring rather than precise time measurement.

The dynamics described in Figure 3 could address the subjective feeling of a continuous flow of time and the duration of the experienced moment. The continuous flow of time is then due to the evolving mental contents in the cortex, overlapping like strands in a rope to create a coherent whole. The duration of the experienced moment is then determined by the potentiation duration of neural ensembles, which can be activated or reactivated by ongoing propagations. This distinction means that the duration of the experienced moment and the evaluation of the rate of time's passage could be nearly completely separated. In normal functioning, these mechanisms are conjectured to overlap substantially, but in altered states of consciousness, they could become desynchronized.

The proposed models and mechanisms provide the beginnings of a possible comprehensive framework for understanding time consciousness and integrating biological processes with the subjective phenomenal experience of time. It is critical to note that the entirety of the work presented here is theoretical, and as such will be very limited without the benefit of additional empirical testing and validation. That being said, all the pathways mentioned here and the direction of activation are consistent with known tractography and anatomical evidence.



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