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# A Conceptual Framework for Relativistic Neuroscience: Temporal Layer Decoupling During Extreme Time Dilation

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**ABSTRACT**

The personal experience of time during extreme perspective-dependent conditions remains poorly understood at the convergence of physics and neuroscience. We present an abstract framework that differentiates four temporal variables external coordinate time, traveller proper time, neural execution time, and perceptual time to analyse the conditions necessary for conscious experience during high-velocity transit. Our analysis exemplifies that, while special relativity forecasts dramatic time dilation in the traveller's frame, all biological processes remain constrained by the traveller's proper time. We derive the minimum proper time threshold (~50–100 ms) required for conscious apprehension based on neural dynamics fluctuations and show that near-light-speed travel over interstellar distances can provide adequate proper time for rich individualised experiences, whereas certain spacetime continuum shortcuts may not. We connect this paradigm to terrestrial analogues in neuropsychiatric pathologies, where temporal processing layers decouple, and propose biomedical engineering approaches for consciousness monitoring during future astronautics. The framework generates testable projections through computational neuroscience simulations, virtual reality projections, and patient studies. We explicitly acknowledge the risky nature of wormhole applications and the dearth of direct experimental validation for relativistic consciousness studies.

***Keywords:*** Relativistic neuroscience, Time dilation, Proper time, Neural oscillatory dynamics, Consciousness monitoring.

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## 1. Introduction

### 1. 1. The Problem of Time in Relativistic and Biological Frames

Time is conceived fundamentally differently across academic disciplines. In classical Newtonian physics, time was deemed absolute and universal (Newton, 1687). Einstein's theories of distinctive (Einstein, 1905) and general (Einstein, 1916) relativity founded that time is relative, observer-dependent, and closely linked with space in a four-dimensional spectrum. Under relativistic conditions particularly at velocities approaching the speed of light ($c \approx 3 \times 10^8$ m/s) or in strong gravitational fields time dilates according to the electromagnetic transformation.

Simultaneously, neurobiology has revealed that the brain's awareness of time is neither absolute nor directly associated with physical clock time (Eagleman, 2008; Wittmann, 2013). Humans exhibit methodical temporal distortions: exaggeration during novel or intimidating experiences, understatement during flow states, and biases in reflective judgements (Wittmann, 2013). The neural mechanisms underlying temporal processing involve distributed networks spanning the basal ganglia, cerebellum, prefrontal cortex, and parietal regions (Buhusi & Meck, 2005; Merchant et al., 2013). Neural signal transmission occurs at velocities ranging from 0.5 to 120 m/s, roughly six to nine orders of magnitude slower than light (Purves et al., 2001).

A conceptual question appears when these domains intersect: What are the necessary and adequate conditions for conscious experience during drastic relativistic travel? According to special relativity, as velocity approaches $c$, the Lorentz factor $\gamma = [1 - (v/c)^2]^{-1/2}$, grows without bound. For a traveller moving at $v = 0.999999c$, $\gamma \approx 707$, meaning that one year of coordinate time matches to approximately 12.4 hours of proper time. From the traveller's perspective, their own neural processes proceed normally; there is no contradiction within the traveller's rest frame. However, the extreme condensation of proper time relative to coordinate time raises questions about the minimum proper time required to sustain conscious awareness and whether certain transit scenarios, particularly those involving spacetime shortcuts, might fall below this threshold.

### 1. 2. Current Gaps in the Literature

Despite extensive research in relativistic physics and neuroscience, integrated models addressing this junction remain sparse. Physics literature focuses on the mathematical formalism of time dilation and spacetime geometry (Carroll, 2004; Misner et al., 1973), while neuroscience investigates temporal perception primarily under terrestrial conditions (Ivry & Schlerf, 2008; Matthews & Meck, 2016). Recent work has explored how altered gravitational fields affect neural function (Clément & Reschke, 2008; Manzey & Lorenz, 1998), and there is growing interest in cognitive challenges during extended spaceflight (Van Ombergen et al., 2017; Zivi et al., 2026). However, no comprehensive framework currently:

- Formally differentiates between coordinate, proper, neural, and sensory time under relativistic conditions;
- Derives minimum proper time boundaries for consciousness from neurobiological constraints;
- Connects relativistic time dilation to known mechanisms of neural temporal processing;
- Proposes biomedical engineering protocols for tracking temporal consciousness during space travel.

### 1. 3. Objectives and Scope

This paper proposes a conceptual framework differentiating four temporal layers: External Coordinate Time ($T_{\text{coord}}$), Traveller Proper Time ($T_{\text{proper}}$), Neural Processing Time ($T_{\text{neuro}}$), and Perceptual Time ($T_{\text{percept}}$). Our central hypothesis states that during extreme relativistic events, these layers exhibit relative disconnecting: while $T_{\text{coord}}$ and $T_{\text{proper}}$ diverge according to benchmark relativistic equations, $T_{\text{neuro}}$ remains constrained by $T_{\text{proper}}$, and $T_{\text{percept}}$ emerges as a cognitive construction modulated by attention, memory, and affective state.

We directly note that this framework is theoretical and hypothetical. It does not claim to "resolve" any paradox (as none exists within standard special relativity), nor does it assert experimental validation. Rather, it provides a structured approach to asking testable questions about consciousness under conditions that may eventually be encountered during interstellar spaceflight.

The rest of this paper is organised as follows: Section 2 develops the theoretical framework for our temporal model. Section 3 presents the integrated biophysical analysis and applies it to transit scenarios. Section 4 discusses the implications for neuroscience, space travel, and biomedical engineering, including constraints. Section 5 provides finalizing remarks.

## 2. Theoretical Framework: A Multi-Layered Model of Time

### 2. 1. Physical Time: Coordinate and Proper Time

#### 2. 1. 1. Special Relativistic Time Dilation

Physical time in relativity is not a single quantity; rather, it must be carefully designated with respect to an observer's reference frame. Coordinate time ($t$ or $T_{\text{coord}}$) is the time measured by a clock in an inertial reference frame (e.g., Earth). Proper time ($\tau$ or $T_{\text{proper}}$) is the invariant time measured by a clock moving with the traveller along its worldline.
For an object moving at constant velocity $v$ relative to a stationary inertial observer, the relationship between coordinate time interval $\Delta t$ and proper time interval $\Delta\tau$ is given by the Lorentz transformation (Einstein, 1905).

$$\Delta\tau = \Delta t\sqrt{1-\frac{v^2}{c^2}} = \frac{\Delta t}{\gamma} \tag{1}$$

where the Lorentz factor is:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \tag{2}$$

Equation (1) reveals that as $v \to c$, the proper time experienced by the traveller approaches zero for any finite coordinate time interval. Table 1 illustrates this relationship across various velocities.

**Table 1.** Time dilation at various velocities. The coordinate time interval is fixed at $\Delta t = 1$ year (Earth observer).

| $v/c$ | $\gamma$ | $\Delta\tau/\Delta t$ | $\Delta\tau$ (traveller) |
|---|---|---|---|
| **0.5** | 1.155 | 0.866 | 10.4 months |
| **0.9** | 2.294 | 0.436 | 5.2 months |
| **0.99** | 7.089 | 0.141 | 1.7 months |
| **0.999** | 22.366 | 0.045 | 16.3 days |
| **0.9999** | 70.712 | 0.014 | 5.2 days |
| **0.99999** | 223.607 | 0.0045 | 1.6 days |
| **0.999999** | 707.107 | 0.0014 | 12.4 hours |

Note that at $v = 0.999999c$, the Lorentz factor is $\gamma \approx 707$ (not 22,360, as might be obtained by miscounting nines). This value is used in all subsequent calculations. The nonlinear growth of the Lorentz factor with velocity is illustrated in **Figure 1.**

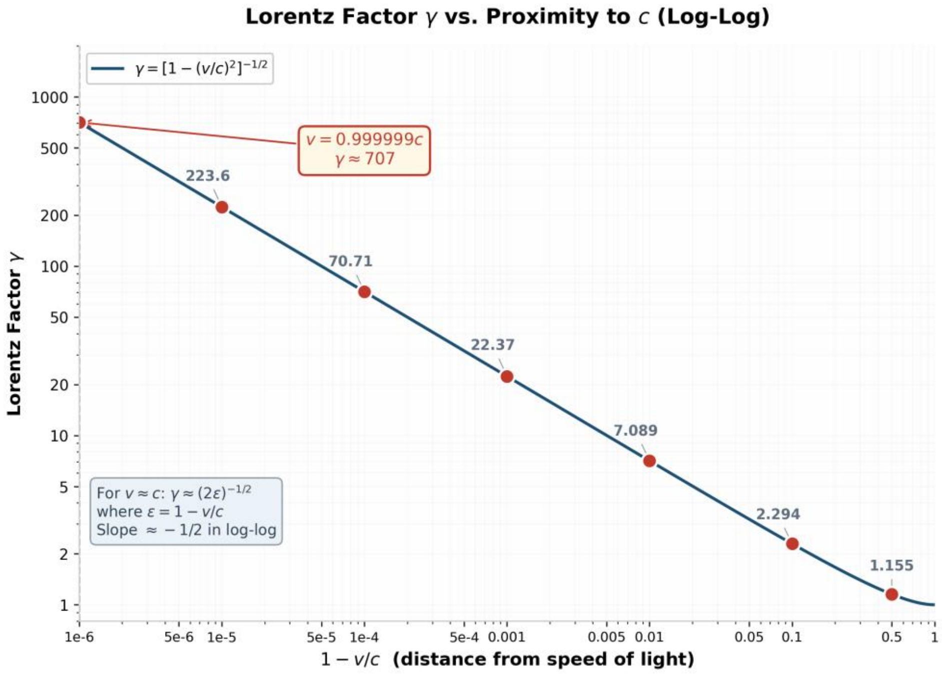


**Figure 1.** Lorentz factor γ as a function of nearness to the speed of light, plotted as γ versus $1 - v/c$ on logarithmic axes.

The linear behaviour in log–log space reveals the approaching power-law scaling $\gamma \sim (2\epsilon)^{(-1/2)}$ for $\epsilon = 1 - v/c \ll 1$. General relativity expands this framework to include gravitative time dilation. Near a massive object, the Schwarzschild metric gives:

$$d\tau = dt\sqrt{1 - \frac{2GM}{rc^2}} \tag{3}$$

where $G$ is the gravitative constant, $M$ is the mass, and $r$ is the radial coordinate. Near the event horizon ($r \to 2GM/c^2$), proper time expansion becomes infinite relative to coordinate time.

### 2. 1. 2. Wormholes and Spacetime Shortcuts: A Boundary Condition Analysis

Morris and Thorne (1988) Proven that Einstein's field equations permit crossable wormhole solutions (Morris & Thorne, 1988). The proper distance $l$ along a wormhole throat introduces a transit time:

$$T_{\text{proper}} \approx \frac{l}{v_{\text{traverse}}} \tag{4}$$

For a throat of length $l = 100$ m traversed at $v = 0.99c$, the proper time is approximately 337 ns. This duration is $\sim 7.4 \times 10^4$ times shorter than the ~25 ms period of a gamma oscillation, which is the minimum temporal unit of aware perception. Consequently, such traversal would provide inadequate proper time for neural processing, and we speculate that conscious experience could not be prolonged during the transit itself.

We highlight that wormhole physics remains entirely hypothetical. We include it not as a realistic situation, but as a limiting condition analysis to exemplify how our framework differentiates between transit situations that do and do not permit conscious experience.

### 2. 2. Neural Processing Time: Biological Constraints

Neural processing time ($T_{\text{neuro}}$) represents the time required for neural signals to propagate and for the brain to integrate information. Unlike coordinate time, $T_{\text{neuro}}$ is not an independent temporal dimension but unfolds within the traveller's proper time. All neural processes—including action potentials, synaptic conveyance, and oscillatory dynamics—experience identical relativistic effects as the rest of the traveller's body. From the traveller's viewpoint, neural activity proceeds at its characteristic biological rate; there is no "extra" processing time available beyond $T_{\text{proper}}$.

#### 2. 2. 1. Neural Signal Propagation

Action potentials propagate along axons at velocities determined by diameter and myelination. Transmission velocity can be approximated by:

$$v_{\text{neuro}} = k.d \tag{5}$$

where $d$ is the axon diameter and $k \approx 6$ m/s/$\mu$m for myelinated fibres (Purves et al., 2001) In humans, velocities range from 0.5-2 m/s (unmyelinated C fibres) to 70-120 m/s (myelinated A$\alpha$ fibres). The fastest signals travel at approximately 120 m/s- $2.5 \times 10^6$ times slower than light.

#### 2. 2. 2. Synaptic and Network Delays

Each synapse introduces a delay of approximately $0.5 - 2$ ms due to neurotransmitter release, diffusion, and receptor binding. For a neural circuit involving $N_s$ synapses with an average delay $\tau_{\text{syn}}$, the total synaptic transmission time is:

$$T_{\text{syn}} = N_s \cdot \tau_{\text{syn}} \tag{6}$$

Complex cognitive processes may involve dozens to hundreds of synaptic steps, creating processing requirements of tens to hundreds of milliseconds.

#### 2. 2. 3. Neural Oscillations and the Temporal Window of Consciousness

The brain processes information through synchronised oscillations at characteristic frequencies (Buzsáki & Draguhn, 2004):

- Delta (0.5 - 4 Hz): Deep sleep
- Theta (4 - 8 Hz): Memory encoding
- Alpha (8 - 13 Hz): Sensory inhibition
- Beta (13 - 30 Hz): Active cognition
- Gamma (30 - 100 Hz): Conscious perception, binding

Gamma oscillations (30 - 100 Hz) are particularly relevant, as they represent the smallest temporal window associated with conscious perception, with a period of 10 - 33 ms (Pöppel, 2009). We propose that a minimum proper time threshold for conscious experience is:

$$T_{\text{proper}}^{\text{min}} \approx 2 - 4 \ \times T_\gamma \approx 50 - 100 \ ms \tag{7}$$

This corresponds to 2 – 4 gamma cycles, allowing for minimal perceptual integration and temporal binding (Pöppel, 1997). If $T_{\text{proper}} < T_{\text{proper}}^{(\text{min})}$, the model predicts that conscious experience cannot be sustained.

#### 2. 2. 4. Mathematical Model and the Proper Time Constraint

For a sequence of $N_e$ cognitive events, each requiring pathway length $L_i$, signal velocity $v_{\text{neuro}}$, $S_i$ synaptic steps, and processing time $\tau_{\text{proc},i}$, the total neural processing time is:

$$T_{\text{neuro}} = \sum_{i=1}^{N_e} \left( \frac{L_i}{v_{\text{neuro}}} + (S_i \times \tau_{\text{syn}}) + \tau_{\text{proc},i} \right) \quad (8)$$

Critically, all neural processing is constrained by the available proper time:

$$T_{\text{neuro}} \leq T_{\text{proper}} \quad (9)$$

This inequality reflects the fundamental physical reality that neural computation cannot exceed the invariant time along the traveller's worldline. The brain's massively parallel architecture allows substantial computation within a given proper time interval, but it cannot create time that does not exist in the traveller's frame.

### 2. 3. Perceptual Time: The Subjective Construction

Perceptual time ($T_{\text{percept}}$) represents the subjective, conscious experience of duration. It is not a direct readout of physical time but a cognitive construction influenced by attention, emotional arousal, memory encoding, and cognitive load (Block et al., 2010; Droit-Volet & Meck, 2007; Ornstein, 1975; Tse et al., 2004).

#### 2. 3. 1. Neural Correlates and the Internal Clock Model

Functional neuroimaging identifies key regions in temporal processing (Coull et al., 2004; Wiener et al., 2010), including the basal ganglia (interval timing), cerebellum (millisecond timing), prefrontal cortex (working memory for temporal information), and parietal cortex (spatial-temporal integration). The "internal clock" model proposes a pacemaker-accumulator mechanism where subjective duration depends on pulse accumulation (Gibbon et al., 1984).

#### 2. 3. 2. Pathological Decoupling: Terrestrial Analogues

Temporal perception abnormalities in neuropsychiatric conditions provide evidence for the disposability of $T_{\text{neuro}}$ and $T_{\text{percept}}$:

- **ADHD:** Consistent time underestimation and impaired temporal foresight (Barkley et al., 1997), suggesting accumulator dysfunction.
- **Depression:** Subjective time slowing (Kitamura & Kumar, 1982), possibly reflecting increased attention to internal states.
- **Schizophrenia:** Deficits in temporal order judgement and duration estimation (Volz et al., 2001), associated with disrupted gamma and theta oscillations.
- Parkinson's disease: Impaired interval timing following dopaminergic degeneration (Malapani et al., 1998).

We emphasise that these disorders involve biochemical, oscillatory, and attentional mechanisms—not relativistic effects. They serve as terrestrial analogues illustrating how $T_{\text{neuro}} \rightarrow T_{\text{percept}}$ decoupling can occur, but not as direct equivalents to relativistic scenarios.

### 2. 3. 3. Phenomenological Model

We represent $T_{\text{percept}}$ as a transformation of $T_{\text{neuro}}$ modulated by cognitive state:

$$T_{\text{percept}} = f(T_{\text{neuro}}; \alpha, \epsilon, \mu, \chi) \tag{10}$$

where $\alpha$ (attention), $\epsilon$ (emotional arousal), $\mu$ (memory encoding), and $\chi$ (cognitive load) are dimensionless modulation factors. A simplified linear approximation is:

$$T_{\text{percept}} \approx \alpha \cdot \epsilon \cdot \mu \cdot \chi \cdot T_{\text{neuro}} \tag{11}$$

Under normal conditions, $\langle \alpha\epsilon\mu\chi \rangle \approx 1$, giving $T_{\text{percept}} \approx T_{\text{neuro}}$. Extreme states can produce significant deviations. **Figure 2** illustrates how the ratio $T_{\text{percept}}/T_{\text{neuro}}$ varies with attention and affective arousal under normal retention and cognitive load conditions ($\mu = \chi = 1.0$).

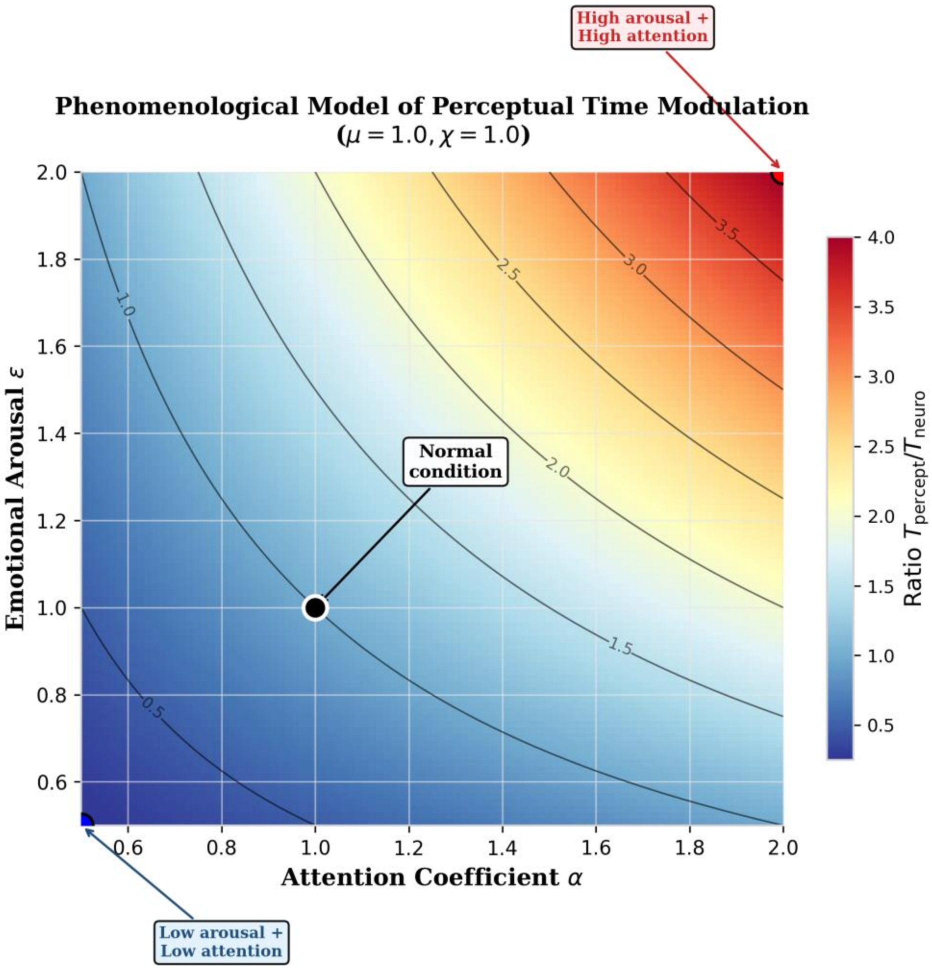


**Figure 2.** Phenomenological model of perceptual time modulation. The heatmap shows the ratio Tpercept / Tneuro as a function of the attention coefficient α and affective excitement ϵ, with μ = χ = 1.0. Contour lines indicate constant ratio values. The black ring marks the normal condition (α = ϵ = 1.0, ratio = 1.0). The red circle shows high arousal and high attention (α = ϵ = 2.0, ratio = 4.0), corresponding to subjective time growth. The blue circle indicates low excitement and low focus (α = ϵ = 0.5, ratio = 0.25), corresponding to subjective time compression.

We directly note that Eq. 11 is a phenomenological model intended to illustrate conceptual relationships, not a quantitatively predictive equation. The coefficients lack unique operational definitions and would require extensive empirical calibration for specific applications.

## 3. The Integrated Biophysical Model and Transit Scenarios

### 3. 1. Hierarchical Relationships and Constraints

The four temporal layers form a strict hierarchy with constraints:

$$T_{\text{coord}} \xrightarrow{\text{Lorentz}} T_{\text{proper}} \xrightarrow{\text{Biology}} T_{\text{neuro}} \xrightarrow{\text{Cognition}} T_{\text{percept}} \quad (12)$$

with the critical constraint $T_{\text{neuro}} \leq T_{\text{proper}}$. Physical time provides the spacetime framework, neural processing operates within that framework, and perceptual time emerges from neural activity.

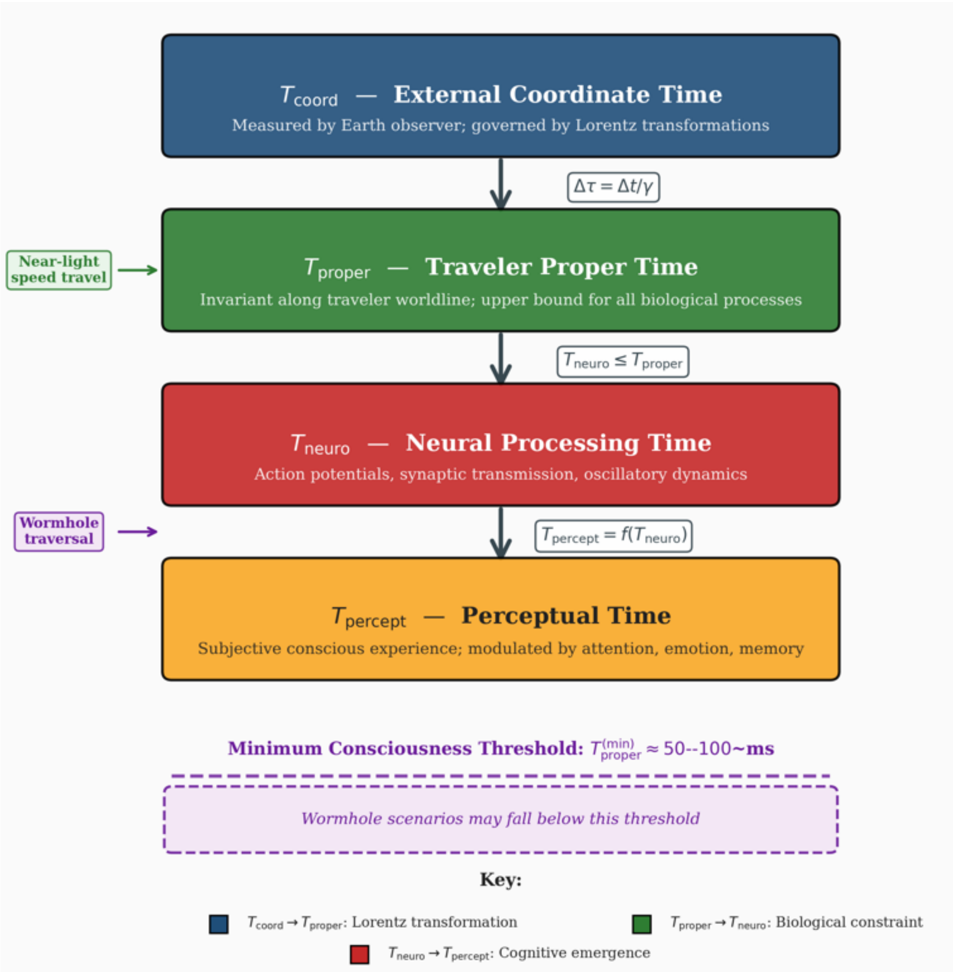


**Figure 3.** Layered model of temporal layers. External align time (Tcoord) is transformed by unique relativity into the traveller's appropriate time (Tproper). Neural processing time (Tneuro) is constrained to not exceed Tproper. Perceptual time (Tpercept) emerges from Tneuro through mental modulation. The minimum boundary for awareness (~50 – 100 ms) is indicated. Wormhole scenarios may fall below this threshold.

### 3. 2. Case Study: Near-Light-Speed Interstellar Transit

Consider a journey of $D = 10$ light-years at $v = 0.999999c$:

Coordinate time (Earth observer):

$$T_{\text{coord}} = \frac{D}{v} \approx \frac{10\ ly}{0.999999\text{c}} \approx 10\ years \tag{13}$$

Proper time (traveler):

$$T_{\text{proper}} = \frac{T_{\text{coord}}}{\gamma} = \frac{10\ years}{707.1} \approx 12.4\ hours \tag{14}$$

Neural processing capacity: With $T_{\text{proper}} \approx 12.4$ hours $= 44{,}640$ s, and a gamma cycle period $T_\gamma = 1/40$ Hz $= 25$ ms:

$$N_\gamma = \frac{T_{\text{proper}}}{T_\gamma} = \frac{44{,}640\ \text{s}}{0.025\ \text{s}} \approx 1.79 \times 10^6 \tag{15}$$

The traveller has approximately 1.8 million gamma cycles available. Given the brain's parallel architecture ($\sim 10^{11}$ neurones, $\sim 10^{15}$ synapses), this provides substantial computational capacity for rich conscious experience. The constraint $T_{\text{neuro}} \leq T_{\text{proper}}$ is easily satisfied. The dramatic difference between coordinate time and proper time, and the resulting neural processing capacity, is visualised in **Figure 4**.

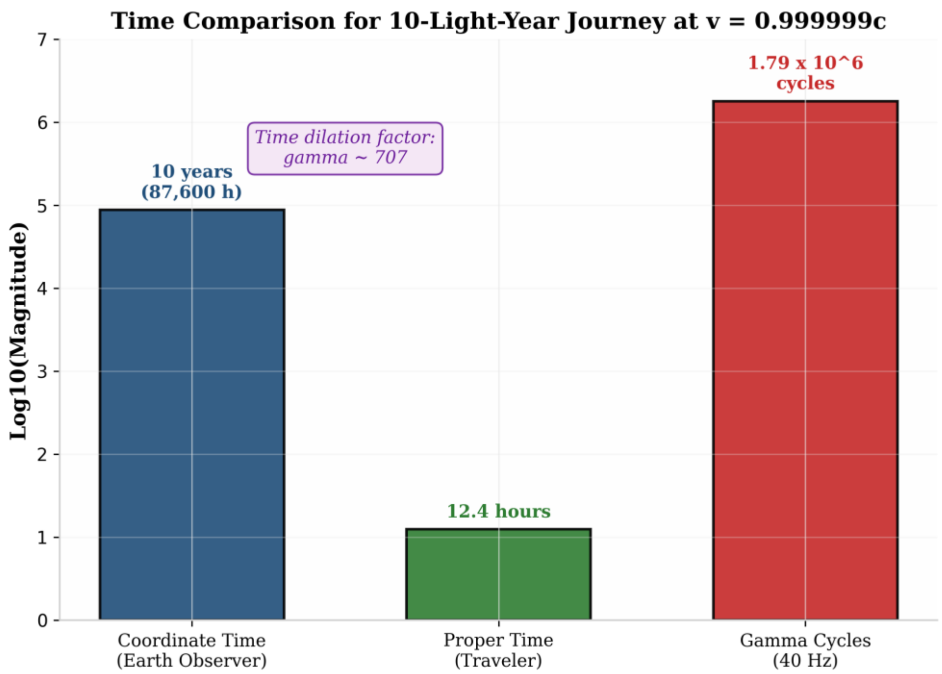


**Figure 3.** Contrast of temporal scales for a 10-light-year journey at $v$ = 0.999999c. The coordinate time seasoned by the Earth observer (10 years) is compressed by a factor of γ ≈ 707 to 12.4 hours of proper time for the traveller. Within this proper time, the brain can complete approximately 1.79×106 gamma cycles (40 Hz), providing substantial computational capacity for conscious knowledge.

Memory formation: Working memory and sensory integration operate on millisecond-to-second timescales and can occur during transit. Long-term memory integration (requiring seconds to hours via synaptic potentiation and hippocampal-cortical dialogue) may be partially limited. The traveler may retain vivid impressions rather than detailed episodic memories.

### 3. 3. Case Study: Wormhole Traversal as Boundary Condition

For a hypothetical wormhole with throat length $l = 100$ m traversed at $v = 0.99c$:

$$T_{\text{proper}} = \frac{100\ m}{0.99\ \times 3 \times 10^8 \frac{m}{s}} \approx 3.37 \times 10^{-7} s \approx 337\ ns \quad (16)$$

This is $\sim 7.4 \times 10^4$ times shorter than the ∼25 ms gamma period. Therefore:

$$T_{\text{proper}} \ll T_{\text{proper}}^{(min)} \rightarrow \text{No sustained conscious experience} \quad (17)$$

The traversal would be experienced as effectively instantaneous. For conscious experience to be possible during wormhole transit, the geometry would need to provide considerably greater proper time (e.g., throat length $\gtrsim 30{,}000$ km at $0.99c$ yielding $\gtrsim 0.1$ s).

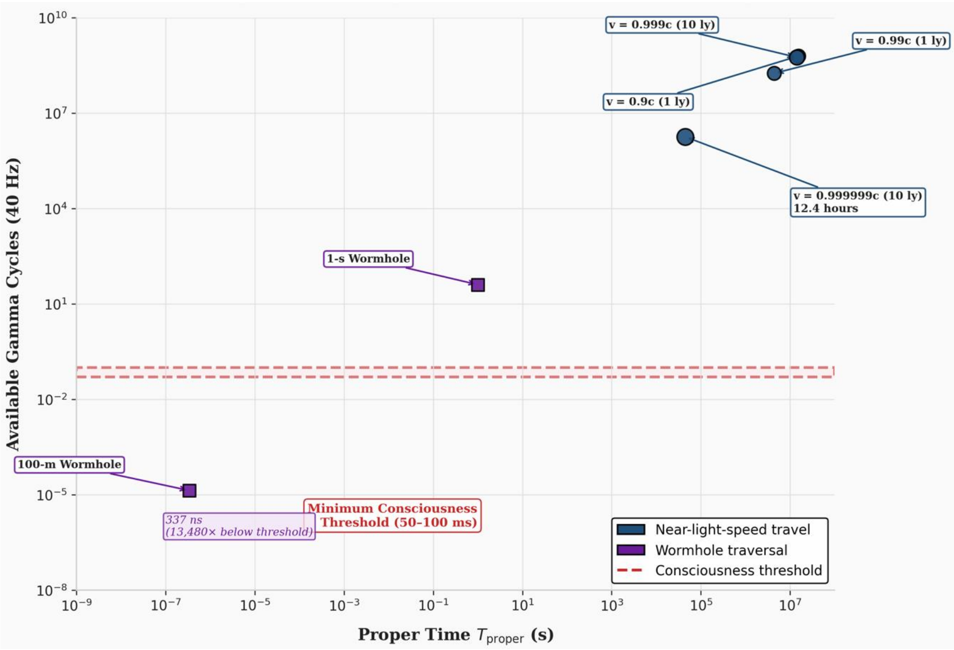


**Figure 4.** Relationship between proper time and available gamma cycles (40 Hz) across transit scenarios. The red dashed line indicates the minimum threshold for conscious experience (∼50 – 100 ms, 2 – 4 gamma cycles). The 100-m wormhole scenario falls far below the threshold, while near-light-speed travel provides ample proper time.

### 3. 4. Testable Predictions and Validation Protocols

We distinguish between near-term and long-term testable predictions:

### 3. 4. 1. Near-Term Predictions (Virtual Reality and Patient Studies)

P1 (VR Paradigm): Virtual reality experiments simulating time dilation effects should demonstrate that participants' neural processing times (measured via EEG/MEG) remain unchanged in their local reference frame, while perceptual time estimates shift. Validation: Compare EEG gamma power and reaction times against subjective duration reports under simulated dilation.

P2 (Patient Studies): Patients with temporal processing disorders should show specific patterns of neural oscillation disruption corresponding to the $T_{\text{neuro}} \rightarrow T_{\text{percept}}$ transformation. Validation: Correlate gamma/theta band abnormalities with duration estimation tasks in ADHD, depression, and schizophrenia cohorts.

### 3. 4. 2. Long-Term Predictions (Spaceflight and Computational Models)

P3 (Spaceflight): During high-speed transit (even at sub-relativistic speeds), astronauts should show normal neural processing times as measured by EEG but altered circadian rhythms due to changed external time cues. Validation: Longitudinal EEG and cognitive assessment during deep-space missions.

P4 (Computational): Biologically realistic neural network simulations under simulated relativistic conditions should confirm that information processing time remains constant in the network's reference frame. Validation: Implement spiking neural networks with appropriate time constants and measure internal processing vs. external time dilation.

## 4. Discussion

### 4. 1. Implications for Neuroscience

### 4. 1. 1. A Taxonomy for Temporal Processing Disorders

Our framework suggests a taxonomy for disorders involving temporal processing:

- **Type 1 ($T_{\text{neuro}}$ dysfunction):** Parkinson's disease, ADHD—pathological changes in pacemaker-accumulator mechanisms.
- **Type 2 ($T_{\text{neuro}} \rightarrow T_{\text{percept}}$ decoupling):** Depression, schizophrenia—intact neural timing but distorted subjective experience via attentional/emotional modulation.
- **Type 3 ($T_{\text{proper}} \rightarrow T_{\text{neuro}}$ constraint violation):** Hypothetical relativistic scenarios where proper time is insufficient for required neural processing.

This classification may guide targeted interventions: dopaminergic agents for Type 1, cognitive training for Type 2, and, speculatively, neurotechnological interfaces for Type 3.

### 4. 1. 2. The Temporal Binding Problem

Our model raises questions about how the brain integrates information across temporal scales. We propose that temporal binding operates at the $T_{\text{neuro}} \rightarrow T_{\text{percept}}$ interface through nested oscillatory windows (Varela, 1999): gamma (25 – 40 ms) for perceptual moments, theta (125 – 250 ms) for working memory updates, and delta (250 – 2000 ms) for conscious integration.

### 4. 2. Implications for Space Travel and Biomedical Engineering

### 4. 2. 1. Consciousness Monitoring and Preservation

Our framework identifies specific biomedical engineering challenges for interstellar travel:

- **Challenge 1:** Temporal Disorientation. Astronauts experiencing extreme time dilation face a disconnect between $T_{\text{percept}}$ and $T_{\text{coord,Earth}}$. Engineering response: Develop neurotechnological interfaces (augmented reality displays, direct neural feedback) providing real-time synchronisation cues.
- **Challenge 2:** Neural Integrity. Extreme acceleration could compromise neural function. Engineering response: Neuroprotective agents, gel-based suspension systems for mechanical stabilisation, and haemodynamic monitoring maintaining constant cerebral perfusion.
- **Challenge 3:** Consciousness Verification. During transit, standard behavioural assessments may be impossible. Engineering response: Implantable or wearable neural interfaces for real-time monitoring of gamma oscillations and evoked potentials to verify sustained $T_{\text{neuro}}$ within $T_{\text{proper}}$ constraints.

#### 4. 2. 2. Proposed Biomedical Engineering Protocols

We propose the following engineering framework for relativistic spaceflight:

- **Pre-flight baseline:** Establish individual neural timing parameters, including gamma frequency, conduction velocities, and synaptic delays, via high-density EEG and transcranial magnetic stimulation.
- **In-flight monitoring:** Continuous EEG/ECoG monitoring of gamma-band activity (30–100 Hz) to verify $T_{\text{neuro}} \leq T_{\text{proper}}$ and detect consciousness degradation.
- **Adaptive life support:** Closed-loop systems adjusting neuroprotective agent delivery based on real-time neural signal analysis.

Post-flight assessment: Comprehensive neurocognitive evaluation comparing pre- and post-flight temporal processing capabilities.

### 4. 3. Limitations and Future Directions

#### 4. 3. 1. Theoretical Limitations

- **L1:** This framework is conceptual and lacks direct experimental validation. No human has experienced extreme relativistic conditions.
- **L2:** Our neural model simplifies massively parallel, hierarchical processing. Future work should incorporate multi-scale dynamical systems approaches (Breakspear, 2017).
- **L3:** We have not integrated quantum gravitational effects, which may become relevant at Planck-scale regimes.
- **L4:** The mechanism by which neural activity generates consciousness (the "hard problem") remains unspecified. We assume consciousness requires neural activity without asserting a specific mechanism.

#### 4. 3. 2. Future Research

- **Computational neuroscience models:** Biologically realistic spiking neural networks under simulated relativistic time dilation to test prediction P4.
- **VR paradigms:** Immersive environments manipulating apparent time flow while recording EEG/fMRI to test P1.
- **Spaceflight analogs:** Studies in isolation chambers, microgravity (ISS), and centrifuge environments to test temporal perception under altered physical conditions.
- **Mathematical formalization:** Rigorous category-theoretic or fiber bundle formulations of the temporal layer coupling.
- **Integration with predictive coding:** Connections to active inference and Bayesian brain hypotheses about time perception (Friston, 2010).

## 5. Conclusion

The presented conceptual framework distinguishes four temporal layers coordinate time, proper time, neural processing time, and perceptual time to analyse the conditions necessary for conscious experience during extreme relativistic transit. Our analysis yields four principal conclusions:

First, special relativity does not create a paradox for conscious experience in the traveller's frame; rather, it establishes strict constraints. All neural processes are bounded by the traveller's proper time ($T_{\text{neuro}} \leq T_{\text{proper}}$). There is no mechanism by which biological processing can exceed this invariant limit.

Second, we derive a minimum proper time threshold of approximately 50–100 ms (2–4 gamma cycles) for sustained conscious perception. Near-light-speed travel over interstellar distances provides ample proper time (e.g., 12.4 hours for a 10-light-year journey at $0.999999c$), supporting rich subjective experience. Conversely, certain hypothetical spacetime shortcuts may fall below this threshold, predicting absent or degraded consciousness during transit.

Third, neuropsychiatric disorders provide terrestrial analogues for temporal layer decoupling, particularly at the $T_{\text{neuro}} \rightarrow T_{\text{percept}}$ interface. These analogues illustrate mechanisms of temporal distortion without implying that psychiatric conditions involve relativistic physics.

Fourth, we propose specific biomedical engineering protocols for consciousness monitoring during future spaceflight, including neural interface design, real-time gamma-band monitoring, and adaptive neuroprotection systems.

This framework is explicitly hypothetical and is intended to stimulate interdisciplinary research at the physics-neuroscience interface. It generates testable predictions through computational modelling, virtual reality paradigms, and patient studies, while acknowledging that direct validation of relativistic consciousness will require advances in propulsion technology beyond current capabilities.

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### Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

### Data Availability

No empirical data were generated for this conceptual study. All mathematical calculations and theoretical derivations are presented in the manuscript.

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