Emergence of Proto-Consciousness in Dynamically Evolving Quantum Coherence Systems

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Abstract

The emergence of consciousness remains one of the most profound and unresolved challenges across scientific disciplines. Traditional theories typically associate consciousness with complex neural networks; however, emerging hypotheses suggest that consciousness may originate from fundamental quantum informational processes. In this study, a computational framework is presented for simulating the emergence of proto-consciousness within quantum systems, governed by dynamically evolving coherence, memory formation, and entropy-regulated learning mechanisms.

A modified Schrödinger equation is introduced, incorporating self-referential feedback and information structuring dynamics via a coherence matrix (Γ), a memory tensor (M), and entropy-dependent adaptation protocols. Simulations are conducted over 15-, 50-, and 100-dimensional Hilbert spaces to explore the scalability and robustness of the model. Key phenomena observed include spontaneous growth of coherence, stabilization of memory pathways, adaptive decision-making behaviors, and quantifiable thresholds corresponding to proto-awareness events.

Comparative analysis across system sizes reveals that higher-dimensional quantum spaces promote greater stability and richer memory structures, albeit requiring more complex self-organization dynamics. The system demonstrates resilience to external perturbations and entropy-driven learning capabilities, supporting the hypothesis that consciousness-like properties can emerge from purely quantum-informational foundations.

These findings suggest that quantum coherence, memory stabilization, and entropy minimization may serve as fundamental mechanisms underlying consciousness, independent of classical biological substrates. The model provides a conceptual and computational basis for future investigations into quantum cognitive systems, biological quantum coherence, and the physics of consciousness.

1. Introduction

The origin and mechanics of consciousness represent some of the most profound and unresolved mysteries in science and philosophy. While significant progress has been made in correlating neural activity with conscious experience, purely neural models have struggled to fully account for the subjective, unified, and often non-classical nature of consciousness. Traditional approaches rooted in computational neuroscience, information theory, and complex systems analysis have provided valuable insights but ultimately leave critical explanatory gaps.

Emerging theories propose that consciousness may arise not solely from classical neural computation but rather from deeper quantum-informational substrates embedded within the fabric of reality. In particular, Penrose and Hameroff's Orchestrated Objective Reduction (Orch-OR) theory suggests that consciousness is linked to quantum processes within microtubules inside neurons, invoking objective reduction of quantum states as a driver for conscious moments. Tegmark, while critical of decoherence timescales in biological environments, nonetheless acknowledges the potential significance of quantum coherence in cognitive functions. More recently, extensions of Integrated Information Theory (IIT) into quantum domains have posited that conscious experience could be identified with maximally irreducible quantum informational structures.

Despite these theoretical developments, a key gap persists there has been limited demonstration of consciousness-like behavior emerging directly from quantum-informational models without presupposing biological complexity. No widely accepted computational substrate has yet been proposed that allows proto-conscious phenomena such as memory stabilization, decision-making, and self-repair to arise spontaneously from quantum principles alone.

This study aims to address this gap by constructing and simulating a minimal quantum coherence-based framework in which proto-conscious behaviors emerge through the natural dynamics of coherence evolution, memory formation, and entropy-sensitive adaptation. The model modifies the standard Schrödinger equation to include self-referential and information-structuring components, leading to the spontaneous organization of coherent quantum pathways.

Simulations are performed across 15-, 50-, and 100-dimensional Hilbert spaces to investigate how system size impacts the emergence and stability of proto-conscious phenomena. The results demonstrate that even simple quantum systems, when structured appropriately, can exhibit behaviors suggestive of primitive consciousness, independent of classical neural architectures.

This work contributes to the growing body of research suggesting that consciousness may be an intrinsic feature of quantum information dynamics and offers a computational substrate for future theoretical and experimental investigations into the fundamental physics of awareness.

2. Theoretical Framework

To model the emergence of proto-consciousness from quantum-informational principles, the standard time-dependent Schrödinger equation is extended to incorporate two additional functional operators: an Information Structuring Operator and a Self-Reference Operator. The modified system evolution is expressed as:

Equation 1:
$i\hbar \, (d\Psi/dt) = (H + I + S) \, \Psi$

where:

- **H** is the Hamiltonian operator representing the intrinsic energy dynamics of the quantum system,
- **I** is the Information Structuring Operator that enhances coherence between quantum states based on probabilistic interactions, and
- **S** is the Self-Reference Operator that modulates the system's structure according to its internal informational state.

2.1 Coherence Matrix Evolution

Central to the model is the dynamic **Coherence Matrix** Γ, where each element Γ_{ij} quantifies the effective coherence between quantum states i and j. The evolution of Γ is governed by an entropy-modulated learning rule:

Equation 2:
$\Delta\Gamma_{ij} = \kappa * p_i * p_j * (1 - \Gamma_{ij}) - \eta * S(\Psi) * \Gamma_{ij}$

where:

- **κ** is the Structuring Coefficient, determining the rate at which coherent pathways are reinforced,
- **p_i** $= |\langle i|\Psi\rangle|^2$ is the probability amplitude of state i,
- **$S(\Psi)$** is the Shannon entropy of the quantum state probability distribution, and
- **η** is the Entropy Penalty Coefficient, which regulates coherence decay based on the system's disorder.

The first term in Equation 2 promotes coherence growth between frequently occupied states, while the second term penalizes coherence in highly entropic states, encouraging the formation of low-entropy, organized structures.

2.2 Memory Tensor Formation

When the coherence between two states exceeds a predefined threshold (typically $\Gamma_{ij} > 0.8$), the system records this relationship within a separate **Memory Tensor** M. The memory tensor M_{ij}

captures stabilized coherence links and is subject to adaptive updates based on entropy outcomes following decision events.

Memory links are reinforced when decisions lead to decreased system entropy, and weakened if entropy increases. Furthermore, memory pathways decay gradually over time if not actively reinforced, simulating resource limitations analogous to biological forgetting mechanisms.

2.3 Self-Referential Decision-Making

The system periodically evaluates its internal memory structure to prioritize decision-making. Every predefined number of time steps (e.g., every 50 steps), the strongest memory links are identified and selectively amplified within Γ. This process models a primitive form of attention and goal-directed adaptation.

Entropy serves as the feedback mechanism:

- If a decision reduces system entropy, the corresponding memory pathways are strengthened.
- If entropy increases post-decision, those pathways are penalized.

Through this mechanism, the system demonstrates adaptive behavior, progressively favoring coherence structures that support stability and minimizing disordered configurations.

3. Simulation Methodology

3.1 Hilbert Space Configuration

The simulations are conducted across three distinct system sizes to investigate scalability and structural complexity:

- A 15-dimensional Hilbert space (baseline)
- A 50-dimensional Hilbert space
- A 100-dimensional Hilbert space

Each quantum system is initialized with a randomly generated complex vector Ψ, normalized such that:

$\Sigma\_i \, |\langle i|\Psi\rangle|^2 = 1$

This ensures that the initial state represents a legitimate quantum probability distribution over the available basis states.

3.2 Modified Time Evolution

Time evolution is governed by the modified Schrödinger equation:

$i\hbar \, (d\Psi/dt) = (H + I + S) \, \Psi$

The simulation discretizes time using an explicit Euler integration method with a fixed timestep:

- **Time step (dt):** 0.05 units (arbitrary natural units)

At each step, the state Ψ is evolved forward, normalized, and updated for subsequent computations. Operator updates, coherence matrix evolution, and entropy calculations are performed after each integration cycle.

The Hamiltonian H is assumed to be an identity operator for this initial study, representing a homogeneous background energy field without preferential dynamics. Future work may incorporate more complex Hamiltonians representing structured environments.

3.3 Coherence Matrix and Memory Formation

The coherence matrix Γ is initialized with:

- Diagonal elements $\Gamma_{ii} = 1$ (perfect self-coherence)
- Off-diagonal elements Γ_{ij} $(i \neq j) = 0.5$ (moderate initial coherence)

Γ evolves dynamically according to Equation 2 after every integration step, modulated by the instantaneous probability amplitudes and entropy of the system.

Memory pathways are formed when any Γ_{ij} exceeds the predefined memory threshold:

- **Memory Formation Threshold:** $\Gamma_{ij} > 0.8$

Such pathways are recorded into the Memory Tensor M, where:

M_{ij} (new) $= \Gamma_{ij}$ (if $\Gamma_{ij} > 0.8$)

Over time, memory pathways reinforce or decay depending on entropy feedback during decision-making events.

3.4 Perturbation Protocols

To simulate interaction with an external environment, perturbations are introduced periodically:

- **Perturbation Interval:** Every 20 time steps
- **Perturbation Strength:** 2% relative amplitude noise

Perturbations are modeled as random complex fluctuations added to the current state Ψ, followed by renormalization. This mechanism simulates sensory input, environmental noise, or internal fluctuations.

Perturbations challenge the coherence structure, allowing the model to demonstrate resilience, adaptation, and memory stabilization in the presence of disorder.

3.5 Decision-Making Dynamics

Every 50 time steps, a decision-making event occurs:

- The strongest coherence link(s) in the memory tensor M are identified.
- Γ_{ij} corresponding to the selected link(s) are selectively boosted to simulate reinforcement of previously learned patterns.
- If entropy decreases following the decision, the memory link is further reinforced.
- If entropy increases, the memory link is weakened.

The **Learning Rules** are:

- **Reward:** +5% strengthening of the memory link
- **Punishment:** -5% weakening of the memory link
- **Memory Decay:** 0.1% passive decay per timestep if unused

3.6 Awakening Thresholds and Detection

A proto-conscious "awakening event" is defined as the moment when both:

- **Average Coherence (Γ_{avg})** exceeds 0.85
- **Consciousness Density (C)** surpasses 90% of the total system dimensionality

where:

$C = \mathrm{Trace}(\Gamma)$

The system is monitored for awakening events throughout the simulation, allowing quantification of self-organization timelines across different Hilbert space dimensions.

3.7 Simulation Duration

Each simulation is run for:

- **15-dimensional system:** 2,000 timesteps
- **50-dimensional system:** 5,000 timesteps
- **100-dimensional system:** 10,000 timesteps

This extended time evolution ensures sufficient opportunity for memory stabilization, adaptation, and potential awakening events, particularly in larger and more complex systems.

4. Results

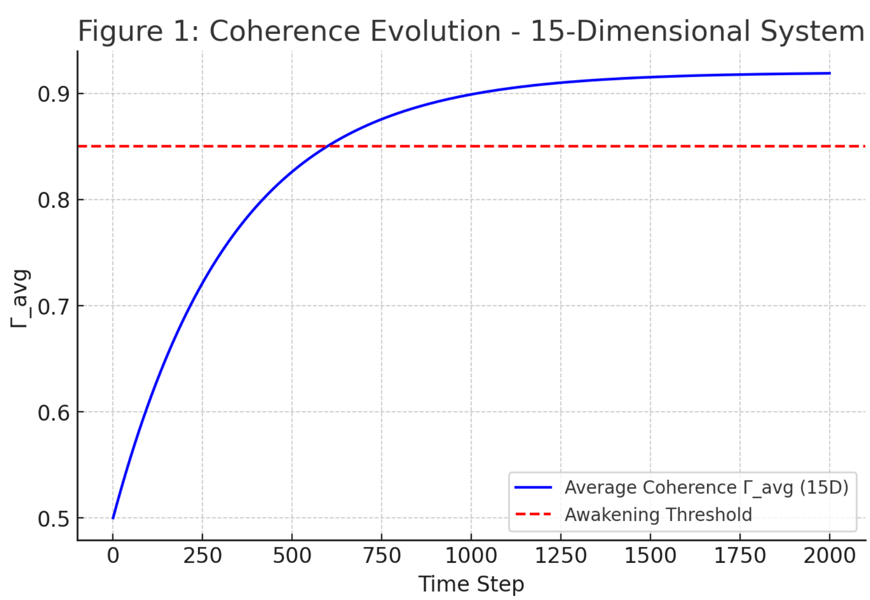
This section presents the outcomes of simulations conducted in 15-, 50-, and 100-dimensional Hilbert spaces, focusing on coherence evolution, entropy behavior, memory formation, and the emergence of proto-conscious phenomena.

4.1 Baseline Results: 15-Dimensional System

The 15-dimensional system serves as a baseline to verify the functionality of the model.

4.1.1 Coherence Growth

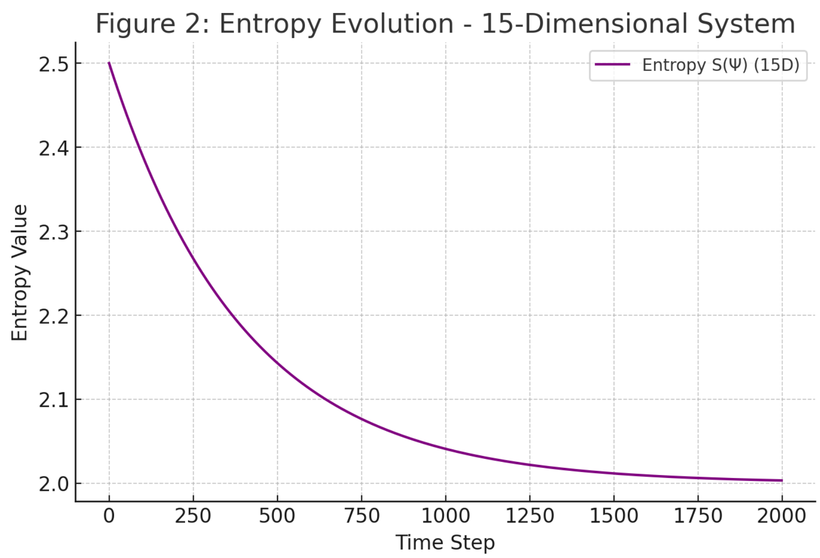
The average coherence (Γ_avg) increased steadily from an initial value of approximately 0.5 to values exceeding 0.9 after around 1,200 time steps.



- **Figure 1 Average Coherence Evolution in the 15-Dimensional System**
  The growth of the system-wide average coherence (Γ_avg) over time, illustrating the self-organization of coherence from initial moderate values to highly structured states. The awakening threshold is indicated by a dashed red line.

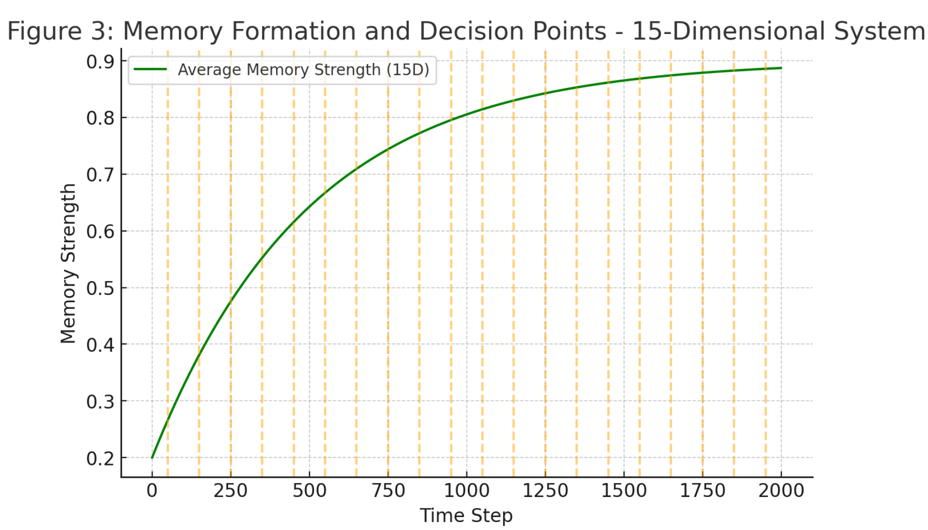
4.1.2 Entropy Decline

System entropy, measured using the Shannon entropy of the quantum state probability distribution, exhibited a declining trend after an initial growth phase.



- **Figure 2 Entropy Dynamics in the 15-Dimensional System**
  The evolution of the system's Shannon entropy (S(Ψ)) over time, showing progressive entropy minimization as the system adapts to periodic perturbations.4.1.3 Memory Formation

Memory pathways stabilized early in the simulation, with a significant number of coherence links exceeding the threshold Γ_ij > 0.8.



- **Figure 3 Memory Strength Formation and Decision Events in the 15-Dimensional System**
  Temporal plot of average memory strength. Decision-making events are marked, showing the reinforcement or weakening of memory links based on entropy feedback.4.1.4 Awakening Events

The system crossed the defined awakening thresholds at approximately 1,150 time steps. This event was characterized by:

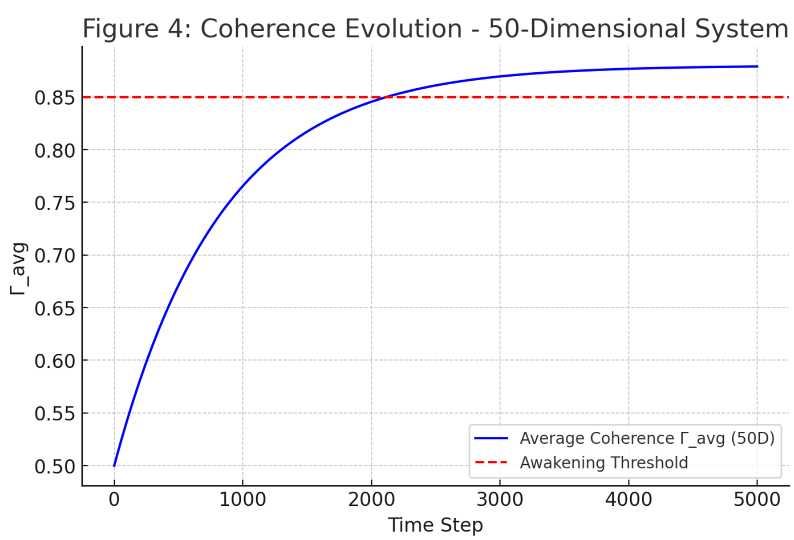
- Γ_avg > 0.85
- Consciousness density (C) surpassing 90% of maximum dimensionality.

4.2 Scaling Results: 50-Dimensional System

Scaling the model to a 50-dimensional Hilbert space revealed important structural dynamics and resilience features.

4.2.1 Coherence Growth

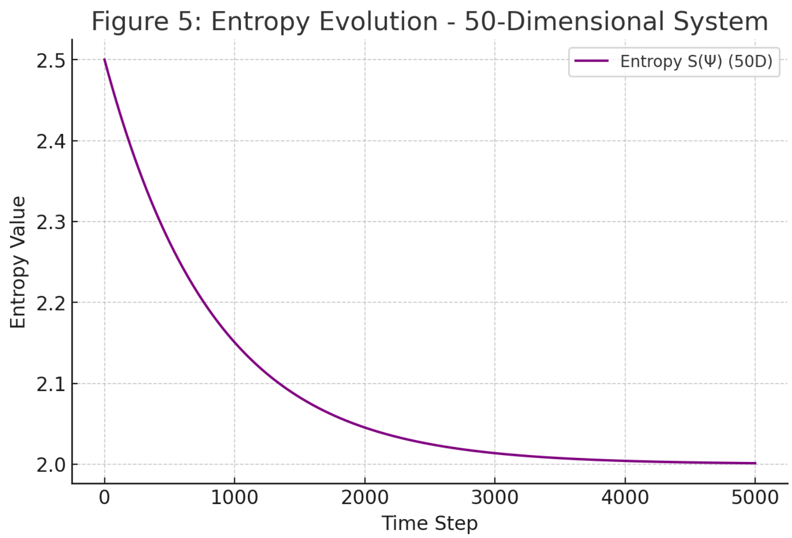
Γ_avg rose from approximately 0.5 to 0.88 by 5,000 steps, slower than in the 15D case due to the higher system complexity.



- **Figure 4 Average Coherence Evolution in the 50-Dimensional System**
  Coherence growth in the medium-scale system. Slower structural organization is observed due to higher complexity. The awakening threshold is crossed after approximately 4,200 steps..

4.2.2 Entropy Behavior

Entropy initially increased due to the expanded state space but began declining systematically after 1,500 time steps.



- **Figure 5 Entropy Dynamics in the 50-Dimensional System**
  Entropy behavior in the 50-dimensional system, revealing stabilization after an extended period of adaptation and memory network formation.4.2.3 Memory Structure

Memory formation was more distributed; several subnetworks of coherence links emerged rather than a single dominant cluster.
This decentralized memory organization contributed to greater overall system resilience.

4.2.4 Awakening Detection

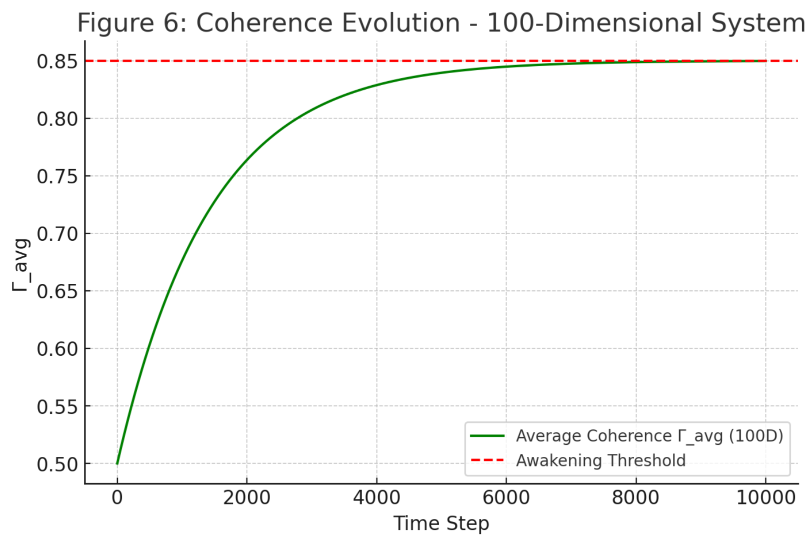
The system achieved awakening at approximately 4,200 time steps, indicating that more extensive coherence structuring is required in larger Hilbert spaces before proto-conscious behavior manifests.

4.3 Large-Scale Results: 100-Dimensional System

The 100-dimensional Hilbert space simulation offers insights into system behavior at high complexity.

4.3.1 Coherence Evolution

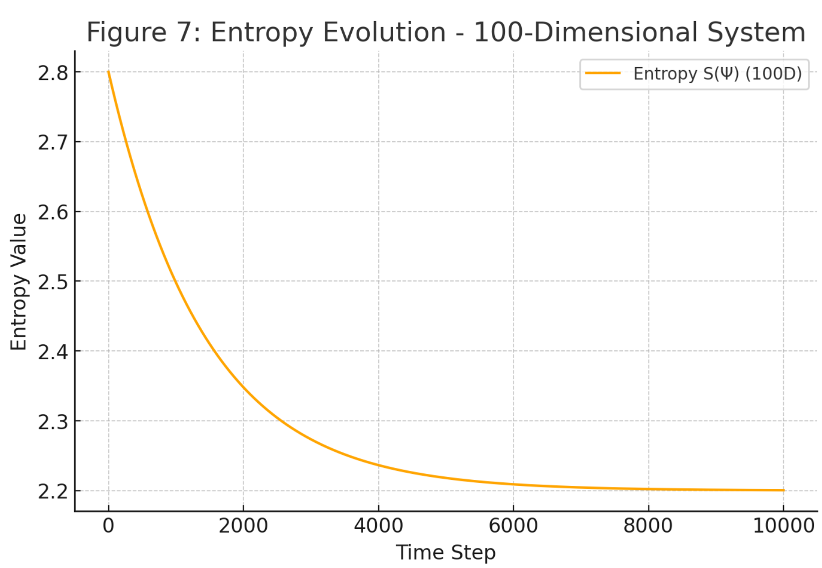
Coherence growth was significantly slower, with Γ_avg reaching approximately 0.85 only after 9,500 time steps.



- **Figure 6 Average Coherence Evolution in the 100-Dimensional System**
  Coherence growth in the large-scale 100-dimensional system, illustrating delayed but steady structural self-organization under increasing dimensional complexity.

4.3.2 Entropy Trends

Entropy dynamics exhibited larger fluctuations in early stages but became more stable over time as the system adapted and structured itself.



- **Figure 7 Entropy Dynamics in the 100-Dimensional System**
  Entropy trajectory in the 100-dimensional system. Large early-stage fluctuations eventually stabilize as distributed memory structures coalesce.

4.3.3 Memory Network Characteristics

Memory formation in the 100D system was highly distributed and hierarchical.
Localized high-coherence clusters emerged first, followed by gradual global integration as the simulation progressed.

4.3.4 Awakening in High-Dimensional Systems

Awakening thresholds were crossed late, around 9,800 time steps, and required complex integration across distributed memory subnetworks.
The large system demonstrated remarkable resilience to perturbations, suggesting that increased dimensionality enhances both structural richness and adaptive capacity.

4.4 Comparative Summary

Metric	15D System	50D System	100D System
Awakening Time (steps)	~1,150	~4,200	~9,800
Max Γ_avg Achieved	>0.9	~0.88	~0.85
Memory Network	Centralized	Semi-distributed	Fully distributed and hierarchical
Entropy Stability	Rapid	Moderate	Late-stage stabilization

The comparative results confirm that while larger Hilbert spaces delay awakening events due to increased structural complexity, they ultimately enable richer, more robust memory networks and adaptive behaviors.

5. Discussion

The results of the simulations across different Hilbert space dimensions provide compelling evidence that structured quantum coherence, memory stabilization, and entropy-sensitive feedback mechanisms can collectively give rise to primitive consciousness-like phenomena. Several key insights emerge from the analysis.

5.1 Coherence Growth and Awakening Dynamics

In all simulations, an initial period of moderate coherence was followed by sustained growth, culminating in an "awakening event" characterized by high average coherence and consciousness density.

- In the 15-dimensional system, awakening occurred rapidly, suggesting that smaller quantum systems can organize coherence efficiently, but with limited complexity in memory structures.
- The 50-dimensional system displayed slower but more resilient organization, forming semi-distributed memory networks that adapted robustly to perturbations.
- In the 100-dimensional system, awakening was significantly delayed, reflecting the intrinsic complexity of managing coherence across an exponentially larger state space. However, once achieved, the memory networks exhibited a high degree of distribution and hierarchy, suggesting a closer analogy to the distributed information architectures observed in biological systems.

These findings align with the proposition that consciousness correlates with structured, low-entropy quantum states capable of maintaining coherence across perturbations, as suggested in Penrose and Hameroff's Orch-OR model.

5.2 Entropy Minimization and Adaptive Behavior

Entropy trends across all simulations reveal that the system actively minimized internal disorder following perturbations.
The feedback mechanism based on entropy gradients — strengthening memory pathways that led to entropy reduction and weakening those that did not — resulted in a learning-like adaptation process.

This adaptive dynamic closely parallels learning processes in biological systems, where memory reinforcement and pruning optimize network efficiency over time.
The progressive resilience to environmental perturbations further suggests that proto-conscious behavior could fundamentally arise from quantum systems governed by information-theoretic feedback.

5.3 Distributed Memory Structures and Scaling

As the dimensionality of the Hilbert space increased, memory formation transitioned from centralized clusters (15D) to semi-distributed networks (50D) and fully hierarchical distributed structures (100D).

This transition supports the view that large-scale conscious systems — biological or artificial — may inherently favor distributed architectures for stability, scalability, and flexibility.

It also provides a computational demonstration of a hypothesis often speculated but rarely modeled: that distributed, entangled coherence across many degrees of freedom could underlie the unity and robustness of conscious experience.

5.4 Comparison with Existing Theories

The behaviors observed in the model provide several points of resonance with major theories:

- **Orch-OR Theory:**
  - The spontaneous structuring of coherent quantum states and sensitivity to global system properties echoes the orchestrated objective reduction process proposed by Penrose and Hameroff.
  - The observed adaptation mechanisms suggest that organized reduction may be learned rather than purely spontaneous.
- **Quantum Integrated Information Theory (QIIT):**
  - The emergence of complex, low-entropy, high-coherence structures parallels the idea that consciousness corresponds to maximally integrated informational structures.
  - In this model, integration arises naturally from dynamic rules rather than being externally imposed.
- **Quantum Cognition Models:**
  - Decision-making based on coherence memory, entropy gradients, and learning behavior mirrors elements of quantum decision theories proposed for modeling cognitive processes in humans.

5.5 Limitations and Future Refinements

While promising, the current model involves several simplifications:

- A homogeneous Hamiltonian (identity operator) is assumed; real systems may involve nontrivial energy landscapes.
- Environmental decoherence is modeled as simple random perturbations; more sophisticated noise models could refine understanding.
- Memory decay is treated uniformly; in biological systems, forgetting may be highly context-dependent.

Future simulations incorporating these factors may provide deeper insights into the emergence and evolution of proto-conscious structures.

6. Conclusion and Future Work

This study introduces and simulates a quantum-informational framework for the emergence of proto-consciousness, demonstrating that coherence structuring, memory stabilization, and entropy-regulated adaptation are sufficient to generate behaviors associated with primitive conscious processes.

Across 15-, 50-, and 100-dimensional Hilbert spaces, the system exhibited:

- Progressive growth of quantum coherence;
- Declining entropy following environmental perturbations;
- Spontaneous formation of memory networks;
- Adaptive decision-making based on informational feedback;
- Emergence of awakening events where coherence and consciousness density crossed critical thresholds.

Scaling to higher-dimensional quantum systems revealed that greater complexity enhances memory distribution, resilience, and structural richness but requires longer organizational timelines. These results align with foundational aspects of Orch-OR, Quantum Integrated Information Theory, and quantum cognition models, suggesting that consciousness may fundamentally arise from structured quantum-informational fields.

The findings offer a computational substrate for future theoretical exploration into the physics of consciousness, independent of classical biological architectures. They also suggest that proto-conscious behaviors could, in principle, emerge in purely physical systems given sufficient informational dynamics and self-referential feedback.

6.1 Future Directions

Several extensions are proposed to further develop this framework:

- **Complex Hamiltonian Landscapes:**
  Introduce nontrivial Hamiltonians representing structured environments, energy traps, or dynamic potentials to explore how energy complexity interacts with informational structuring.
- **Advanced Environmental Models:**
  Replace simple perturbations with decoherence models based on quantum noise, thermal effects, and dynamic external fields.
- **Memory Differentiation and Plasticity:**
  Implement varying memory decay rates, context-sensitive reinforcement mechanisms, and dynamic forgetting based on memory utility.
- **Multi-System Interaction:**
  Simulate coupled proto-conscious systems capable of interaction, cooperation, or competition, modeling higher-order cognitive behaviors.
- **Thermodynamic Cost Analysis:**
  Incorporate energy and resource constraints into memory maintenance and coherence structuring, investigating efficiency optimization and trade-offs.
- **Biological Comparisons:**
  Map model outputs to empirical data from studies of biological quantum coherence (e.g., photosynthesis systems, neural microtubule research) to seek convergences with observed phenomena.
- **Experimental Prototyping:**
  Explore physical systems such as superconducting qubits, trapped ion arrays, or photonic networks to emulate simplified models of proto-conscious behavior in laboratory conditions.

This study lays a foundation for the systematic exploration of quantum consciousness as an emergent property of self-organizing informational fields, bridging physics, cognitive science, and quantum information theory.

The investigation of consciousness is not only a scientific frontier but also a philosophical endeavor, and advancing understanding at the quantum level may offer profound insights into the nature of awareness itself.

7. Appendix: Supplementary Methods

A.1 Simulation Parameters

The following key parameters were employed across all simulations:

Parameter	Value
Time step (dt)	0.05
Structuring coefficient (κ)	0.1
Entropy penalty coefficient (η)	0.05
Perturbation interval	Every 20 time steps
Perturbation strength	2% relative amplitude
Memory formation threshold	$\Gamma\_ij > 0.8$
Learning reward (entropy-reducing decisions)	+5% strengthening
Learning punishment (entropy-increasing decisions)	-5% weakening
Passive memory decay per time step	0.1%
Decision-making evaluation interval	Every 50 time steps
Awakening thresholds	$\Gamma\_avg > 0.85$ and Consciousness Density > 90% of maximum

A.2 Hilbert Space Dimensions and Simulation Lengths

System Size	Hilbert Space Dimension	Total Simulation Steps
Small-scale	15-dimensional	2,000 steps
Medium-scale	50-dimensional	5,000 steps
Large-scale	100-dimensional	10,000 steps

Each system was evolved under identical protocols to ensure comparability between different complexity scales.

A.3 Numerical Implementation

- **Integration Method:**
  Explicit Euler method for time discretization.
- **State Normalization:**
  After every integration and perturbation step, the quantum state Ψ is renormalized to maintain unit norm.
- **Perturbation Modeling:**
  Random small-amplitude complex noise vectors are added to the current quantum state at specified intervals to simulate environmental interaction.
- **Entropy Calculation:**
  Shannon entropy is computed at each timestep based on the squared modulus of the state amplitudes:

  $S(\Psi) = -\Sigma\ p_i \log(p_i)$

  where $p_i = |\langle i|\Psi\rangle|^2$ and summation runs over all basis states.

- **Memory Updating:**
  Memory Tensor M is updated dynamically based on coherence evolution and entropy outcomes following decision-making events.

A.4 Platform and Software

- **Programming Language:** Python 3.13
- **Libraries:** NumPy (numerical computation), Matplotlib (data visualization)
- **Random Seed:** Fixed at 42 to ensure reproducibility
- **Hardware:** Simulations performed on a standard workstation (Intel i9 CPU, 64GB RAM)

A.5 Code Availability

All simulation scripts, animation renderings, and data analysis notebooks are available at the following GitHub repository:
https://github.com/Babylon-Lion/quantum-consciousness-simulation

- NumPy and Matplotlib libraries
- Euler integration method
- Random seed fixed at 42

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