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# The Double-Slit Experiment Is Already Happening in the Brain

## Sleep, Localization, and Active Inference in the Ze Framework

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## Abstract

The double-slit experiment, a cornerstone of quantum mechanics, is traditionally viewed as a paradoxical demonstration of wave-particle duality. This article posits that its core dynamic—superposition, interference, and environment-driven localization—is not a unique quantum phenomenon but a fundamental computational principle implemented by the brain. We introduce the Ze framework, arguing that the brain operates as a biological interferometer. Cognitive systems maintain multiple generative hypotheses in a state of active interference (superposition), analogous to the quantum wavefunction passing through both slits. "Which-path" information, supplied by sensory data, action, and social context, forces cognitive decoherence, localizing perception and decision into a single narrative. Sleep is recast as an intrinsic quantum eraser, periodically degrading which-path information to restore cognitive flexibility and prevent pathological hyper-localization. The framework structurally links quantum decoherence, Bayesian active inference, and the neurobiology of sleep and wake cycles. It provides a transdiagnostic model for psychopathology, where disorders like psychosis and PTSD are seen as dysregulations of this interference-localization cycle. We conclude that the brain does not observe quantum reality; it actively instantiates its core logic, making the double-slit experiment a continuous, lived process of resolving ambiguity to survive and understand the world.

**Keywords**: Active Inference, Cognitive Decoherence, Double-Slit Analogy, Free Energy Principle, Predictive Processing, Sleep, Transdiagnostic Psychiatry.

# The Central Thesis

The quantum double-slit experiment is often presented as a mysterious phenomenon exclusive to the microscopic world, where particles seem to pass through two slits simultaneously, creating an interference pattern unless we "look" at which slit they take. This paper argues that the core *mechanism* of this experiment—the generation, interference, and context-dependent collapse of multiple potential states—is not a quantum curiosity but a fundamental principle of adaptive systems engaged in active inference (Friston, 2010). Specifically, it posits that the adult human brain operates continuously in this double-slit mode. The brain is a system that perpetually constructs multiple, often incompatible, interpretations of sensory data (Hohwy, 2016), minimizes a quantity formally analogous to free energy (Friston & Kiebel, 2009), and is forced by environmental demands to either maintain a superposition of hypotheses or localize onto a single, actionable narrative.

This framework, termed here the Ze framework for its focus on interference (*Z*), proposes that cognition is not a simple feedforward process but a dynamic interference pattern between competing generative models. The "which-path" information that destroys quantum interference finds its cognitive analogue in sensory binding, linguistic framing, goal-directed action, and social feedback—all of which force a path localization (Clark, 2013). Consequently, phenomena like sleep, insight, and even psychopathology can be reinterpreted through the physics of interference and decoherence, suggesting a profound structural isomorphism between the resolution of uncertainty in quantum systems and in the brain (Bruza et al., 2015).

## Interference as a Cognitive State

In the double-slit experiment, a particle's wavefunction passes through both slits, and the amplitudes interfere. In the Ze framework, this interference corresponds to a cognitive state where multiple, mutually exclusive hypotheses about the causes of sensory input are concurrently entertained and remain *active* and *unresolved*. This is not merely parallel processing; it is the maintenance of a probabilistic superposition within the brain's generative model (Knill & Pouget, 2004). The interference pattern manifests as the tension, ambiguity, or creative potential experienced during contemplation, imagination, or dreaming.

Conversely, localization—the appearance of a particle at a single point on the detector—corresponds to perceptual binding, decision-making, or the stabilization of a single narrative ("this is what happened"). This is the brain's equivalent of wavefunction collapse, but it requires no external observer. It emerges naturally when one hypothesis provides a sufficiently better explanation for sensory data, thereby minimizing variational free energy more effectively than its rivals (Friston, 2009). Waking consciousness, with its demand for precise, coordinated action, is largely a localized state where cognitive interference is actively suppressed to avoid paralytic uncertainty (Cisek & Kalaska, 2010). Sleep and certain meditative states, in contrast, permit a resurgence of interference, allowing for the recombination of hypotheses (Lewis et al., 2018).

## "Which-Path" Information and Cognitive Decoherence

In quantum mechanics, acquiring "which-path" information—detecting which slit a particle traverses—destroys the interference pattern. The system is forced into a definite state. In cognition, a similar decoherence mechanism is constantly at play. "Which-path" information is supplied by any process that increases the precision or unambiguousness of a sensory cue, a motor commitment, or a social confirmation (Van de Cruys et al., 2014).

For example, squinting at a distant object, verbalizing a hypothesis, or receiving a confirming nod from a peer all serve as "measurements" that increase the Bayesian precision (inverse variance) afforded to one particular generative model (Feldman & Friston, 2010). As this precision increases, the conflict between competing models rises, and the free energy landscape sharpens around a single minimum. This process of cognitive decoherence—the transition from an interfering superposition to a localized state—is driven by action and engagement with the world (Friston et al., 2016). The more sensory-motor evidence that accrues for a specific "path" of interpretation, the faster and more irrevocable the localization becomes.

## Sleep as a Cognitive Quantum Eraser

The quantum eraser experiment demonstrates that if "which-path" information is recorded but then irreversibly erased before the final detection, the interference pattern can be restored (Walborn et al., 2002). Sleep, particularly slow-wave and REM sleep, performs a strikingly analogous function for the brain (Hobson & Friston, 2012). During sleep, top-down sensory precision is drastically attenuated (the brain disengages from external "measurement"), and the neuromodulatory milieu shifts (e.g., lowered norepinephrine) (Poe et al., 2010). This effectively "erases" the acute which-path information provided by the day's sensorimotor engagements.

The function of this erasure is not to create new data but to allow the synaptic weights and latent representations that underpin generative models to be updated without the pressure of immediate localization (Tononi & Cirelli, 2014). By reducing the free energy difference between competing models, sleep restores the potential for interference. This is crucial for memory consolidation, creativity, and emotional regulation—processes that benefit from the recombination of information without the constraint of having to select a single, immediate action (Lewis et al., 2018). Thus, sleep is not merely passive rest; it is an active periodic reset of the brain's interference capability, a nightly quantum eraser for cognition.

## Two Generative Models and Their Conflict

The Ze framework proposes that the brain implements at least two primary, competing generative models whose interaction produces the interference pattern of cognition. Model **A** is a *forward model*: it is causal, sensorimotor, and pragmatically oriented toward action and survival. It seeks to predict the consequences of actions and to minimize prediction error through movement (Friston et al., 2010). Model **B** is an *inverse model*: it is counterfactual, reconstructive, and oriented toward understanding past causes and imagining possible worlds.

It seeks the best explanation for what has already happened, often in narrative form (Hassabis & Maguire, 2009).

Interference is possible when sensory data is ambiguous enough to be accommodated by both models without forcing a commitment. Localization occurs when the demands of the environment—often mediated through Model A's need for precise action—create an irreconcilable conflict, forcing one model to dominate. This continuous dialectic is the engine of conscious experience, with mental disorders potentially arising from a failure to properly regulate this interference-localization cycle (Sterzer et al., 2018).

The double-slit experiment is not a mere metaphor for cognition; it is a physical prototype of how any system performing active inference on hidden causes must operate. The brain is such a system, where maintaining a superposition of hypotheses (interference) is the default computational strategy, and collapsing onto one (localization) is a necessity imposed by the need to act in a concrete world. This view dissolves the Cartesian theater, replacing it with a physics of perception where sleep acts as a periodic quantum eraser, mental illness reflects a dysregulation of which-path information, and consciousness itself can be understood as the dynamic interference pattern arising between our competing models of reality.

# Interference as a Cognitive State

The central mystery of the quantum double-slit experiment lies in the interference pattern—the observation that a single particle behaves as if it passes through both slits simultaneously, its possible paths superimposing. This paper argues that the brain, in its core computational logic, operates in a regime directly analogous to this quantum phenomenon. Within the proposed Ze framework, cognitive *interference* is not a metaphor but a formal description of a fundamental computational state: the simultaneous, active maintenance of multiple incompatible hypotheses about the world (Friston & Kiebel, 2009). Conversely, cognitive *localization* is the process by which this superposition collapses into a single, stabilized interpretation ("this is what happened"). Understanding this dynamic is key to explaining the spectrum of conscious states, from the focused clarity of wakeful action to the diffuse creativity of sleep and insight.

## Defining Cognitive Interference and Localization

In quantum physics, interference arises from the linear superposition of probability amplitudes. In cognitive neuroscience, a parallel can be drawn to the Bayesian brain hypothesis, where the brain represents beliefs as probability distributions (Knill & Pouget, 2004). Cognitive interference, therefore, occurs when the posterior probability distribution over latent causes (e.g., the identity of an object, the meaning of a sentence, or the memory of an event) is multimodal. The system does not commit to one peak; instead, it maintains the tension between them. This is not indecision but a state of active exploration and parallel evaluation, where the "amplitude" of each hypothesis continues to influence processing (Busemeyer & Bruza, 2012). Evidence from perceptual decision-making tasks shows that the brain can represent multiple action plans in parallel until a threshold is crossed, a state reminiscent of a quantum superposition before measurement (Cisek & Kalaska, 2010).

Localization is the resolution of this superposition. It is the moment when multimodal uncertainty resolves into a unimodal belief, corresponding to perceptual binding, categorical decision, or memory recall. This process is not necessarily conscious but is a mechanistic outcome of belief updating under the free-energy principle, where the brain minimizes surprise by selecting the hypothesis that best explains the sensory data (Friston, 2010). Neurophysiologically, this may correspond to the synchronization of neural assemblies representing the winning hypothesis and the suppression of competing representations (Engel & Singer, 2001).

## States Permitting Interference: Sleep, Imagination, and Insight

Certain brain states are characterized by a heightened tolerance for, or even a promotion of, cognitive interference.

**Seep and Dreaming**: The sleeping brain is the quintessential interference-generating machine. Sensory input from the external world is gated, dramatically reducing the "which-path" information that forces localization in wakefulness (Hobson & Friston, 2012). During REM sleep, in particular, the neuromodulatory environment (high acetylcholine, low norepinephrine) promotes a hyper-associative state. This allows for the recombination of memory traces and concepts in novel, often illogical, ways—a clear signature of interference between disparate cognitive schemata (Lewis et al., 2018). The function of this may be memory consolidation through a process of synaptic renormalization that does not require a single, fixed narrative (Tononi & Cirelli, 2014).

- **Imagination and Mind-Wandering**: The deliberate or spontaneous generation of counterfactual scenarios is another domain of permitted interference. When imagining future events or fictional scenarios, the brain must simultaneously hold in mind both the present reality and the constructed possibility, inhibiting the strong localization to the here-and-now (Buckner & Carroll, 2007). This "default mode" of cognition is supported by a network (including the medial prefrontal cortex and posterior cingulate) that shows increased activity when the brain is not engaged in goal-directed tasks, precisely when interference between internal models can flourish (Raichle, 2015).
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- **Insight and "Aha!" Moments**: The moment of insight often follows a period of impasse, where conscious, localized problem-solving strategies fail. This impasse may reflect excessive localization on an incorrect path. The shift to insight involves a relaxation of top-down constraints, allowing for the interference of remote, weakly associated concepts that were previously suppressed. Neuroimaging studies show a burst of gamma-band activity in the right anterior superior temporal gyrus at the moment of insight, potentially marking the sudden, coherent localization of a new, interference-born solution (Jung-Beeman et al., 2004).

### States Suppressing Interference: Waking Action and Focused Attention

In contrast to the states above, effective interaction with the present environment demands the suppression of interference to enable decisive action.

- **Goal-Directed Wakefulness**: To act efficiently, the brain must localize onto a single, best-guess model of the world and the body's place within it. This is the realm of the dorsal visual stream for sensorimotor control, which requires precise, unambiguous spatial representations (Milner & Goodale, 2008). Action selection itself is a process of localization, where multiple potential motor plans (interference) are resolved into one executed movement (Cisek & Kalaska, 2010). The neuromodulator norepinephrine, central to the brain's arousal systems, is thought to enhance the signal-to-noise ratio of neural processing, effectively sharpening probability distributions and suppressing irrelevant, interfering activity (Aston-Jones & Cohen, 2005).
- **Focused Attention**: Attention acts as a cognitive "which-path" detector. By selectively amplifying the precision (inverse variance) of sensory evidence for one hypothesis over others, attention forces a rapid localization (Feldman & Friston, 2010). This is analogous to placing a detector at a quantum slit: it collapses the possibilities. Studies of binocular rivalry—where perception alternates between two incompatible images presented to each eye—demonstrate that directing attention to one interpretation stabilizes it, prolonging its perceptual dominance and suppressing the interfering rival (Meng & Tong, 2004).

### A Dynamic Spectrum

The brain does not exist in a fixed state of either pure interference or pure localization. Instead, it dynamically navigates a spectrum between these poles, governed by neuromodulatory systems and environmental demands. The Ze framework posits that healthy cognition requires fluid transitions between these states: the capacity for focused localization to act, and the capacity for permissive interference to imagine, create, and integrate. Pathologies of thought, such as the intrusive thoughts of anxiety (excessive, unwanted interference) or the rigid delusions of psychosis (pathological, fixed localization), may arise from a dysregulation of this fundamental dynamic (Sterzer et al., 2018). Thus, the physics of the double-slit experiment provides a powerful lens through which to view the very nature of thought, consciousness, and their alterations.

# "Which-Path" Information in the Brain

In the quantum double-slit experiment, the mere possibility of obtaining "which-path" information—determining through which slit a particle passes—is sufficient to destroy the interference pattern. The system is forced from a superposition of possibilities into a definite, localized state. This paper argues that an isomorphic process of cognitive decoherence is fundamental to brain function. Within the Ze framework, "which-path" information is not a quantum abstraction but a tangible, multi-modal set of constraints that permeate cognition. These constraints—including sensory fixation, linguistic labeling, social feedback, goal-setting, and motor action—serve to increase the precision (or certainty) afforded to one particular generative model of the world, thereby forcing a collapse of competing hypotheses into a single, actionable narrative (Friston, 2010). The brain's continuous processing of such information governs the dynamic transition between the interference of creative thought and the localization necessary for survival.

## The Principle of Cognitive Decoherence

The destruction of quantum interference by which-path information is a canonical example of decoherence, where a quantum system becomes entangled with its environment, losing its phase relations and behaving classically (Zurek, 2003). A formally analogous process, cognitive decoherence, can be understood through the Bayesian brain hypothesis and the free-energy principle (Friston & Kiebel, 2009). Here, the brain's internal generative models constitute the "system," and the sensory-motor stream provides the "environment." As sensory evidence accrues in favor of a specific interpretation (a "path"), the probability distribution over latent causes sharpens. This sharpening increases the precision or inverse uncertainty of the prediction errors associated with alternative models, effectively suppressing their influence—a cognitive analogue of decoherence (Bruza et al., 2015). The "measurement" is not performed by an external observer but is an inherent consequence of the brain's active engagement with the world to minimize free energy (Hohwy, 2016).

## The Modalities of Cognitive "Which-Path" Information

In the brain, which-path information is conveyed through several powerful, interacting channels:

- **Sensory Fixation and Binding**: The act of focusing sensory apparatus—foveating an object, orienting ears, or haptic exploration—provides high-precision, time-locked data that anchors perception to a specific cause. This process of perceptual binding, where features like color, shape, and motion are integrated into a single object, is a potent form of localization. Neurophysiologically, this may be mediated by gamma-band synchronization, which "binds" neural assemblies representing the selected percept while inhibiting others, thereby resolving perceptual interference (Engel & Singer, 2001). Studies of ambiguous figures, like the Necker cube, show that sustained fixation tends to lock perception into one interpretation, acting as a perceptual which-path detector (Meng & Tong, 2004).
- **Linguistic Labeling and Conceptual Commitment**: Language is a supremely effective decoherence mechanism. Attaching a verbal label to an ambiguous stimulus or internal state commits the system to a discrete, categorical schema. This dramatically increases the precision of top-down predictions from lexical-semantic networks, suppressing alternative interpretations. For instance, verbally naming an ambiguous odor powerfully biases and stabilizes its perception (Herz & von Clef, 2001). Language internalized as inner speech may serve a similar function in cognition, structuring thought by sequentially localizing ideas into a linear narrative (Alderson-Day & Fernyhough, 2015).
- **Social Feedback and Shared Reality**: The social environment is a rich source of which-path information. Confirmation, disagreement, or shared gaze from others provides direct Bayesian evidence for or against one's internal hypotheses. The human

brain is exquisitely tuned to such social cues, using them to update its models, often rapidly overriding personal interpretations to align with the group—a process underpinning social conformity and shared reality (Zaki et al., 2011). This social validation acts as a powerful external measurement, collapsing divergent individual interpretations into a consensual, localized narrative.

- **Goal-Directed Action and Motor Commitment**: Perhaps the most fundamental source of which-path information is action itself. Embodied cognition theories posit that cognition is for action (Clark, 2013). Initiating a specific motor plan, such as reaching for one object among several, is the ultimate commitment to a path. The proprioceptive and sensory consequences of the action generate a torrent of precise, reafferent feedback that is uniquely predicted by the motor intention, thereby validating the associated generative model and extinguishing competing action plans (Cisek & Kalaska, 2010). This is captured formally by active inference, where action is seen as a way to selectively sample data that confirms one's predictions (Friston et al., 2016).

## Conflict Acceleration and Rapid Localization

The Ze framework makes a critical prediction: the accumulation of which-path information from multiple, convergent modalities exponentially accelerates cognitive localization. Each modality—sensory, linguistic, social, motor—provides independent yet congruent evidence for a specific "path." This congruence dramatically increases the model evidence (or lowers the free energy) for the leading hypothesis while simultaneously increasing the conflict or divergence of free energy for all alternatives (Feldman & Friston, 2010).

This escalating conflict is computationally expensive and metabolically unsustainable, creating pressure for rapid resolution. The brain's neuromodulatory systems, particularly the locus coeruleus-norepinephrine system associated with arousal and task engagement, are ideally positioned to mediate this rapid transition (Aston-Jones & Cohen, 2005). Norepinephrine is thought to enhance neural gain, effectively increasing the signal-to-noise ratio and sharpening the competition between representations, thus facilitating winner-take-all dynamics that lead to swift localization (Servan-Schreiber et al., 1990). The subjective experience of this process can range from the sudden "click" of perceptual recognition to the decisive moment of choice.

## The Brain as a Self-Decohiring System

The brain is not a passive recipient of which-path information; it is an active seeker and generator of it. Through perception, language, social interaction, and action, the brain continuously performs self-measurement, collapsing its own probabilistic wavefunctions to navigate a concrete world. The delicate balance lies in regulating this decoherence. Optimal cognitive function requires phases where which-path information is relaxed (e.g., in sleep, daydreaming, or brainstorming) to allow for interference and recombination, and phases where it is robustly engaged for decisive action. Dysfunctions in this regulatory balance—such as an inability to suppress irrelevant which-path information in anxiety or an over-reliance on internally generated, fixed paths in psychosis—may lie at the heart of numerous neuropsychiatric conditions (Sterzer et al., 2018). Understanding cognition through the lens of which-path information and decoherence thus unifies phenomena from quantum physics to social psychology, revealing the brain as a masterful orchestrator of its own state of certainty.

## Sleep as a Cognitive Quantum Eraser

In the delayed-choice quantum eraser experiment, the perplexing phenomenon of wave-particle duality is taken a step further: even after a particle has traversed the slits and its "which-path" information has been recorded, this information can be subsequently "erased" by a later measurement choice. Remarkably, this retroactive erasure can restore the interference pattern, demonstrating that the definite state of the system was not finalized until the information became irrevocable (Walborn et al., 2002). This paper posits that sleep—specifically the orchestrated neurophysiology of the sleep cycle—performs a precisely analogous function for the brain. It acts as a cognitive quantum eraser, a periodic, intrinsic mechanism that degrades the "which-path" information accrued during waking life, thereby restoring the potential for cognitive interference. This view reframes sleep's core function: not as a state of passive rest or simple memory consolidation, but as an active process of cognitive de-localization, essential for maintaining the brain’s computational flexibility and long-term stability (Tononi & Cirelli, 2014).

## The Cognitive "Which-Path" Record and its Erasure

During wakefulness, the brain is a relentless accumulator of which-path information. Every committed action, perceptual decision, social exchange, and linguistic label serves as a "measurement," increasing the precision (inverse uncertainty) of specific generative models and sharpening the probability distributions over latent causes (Friston, 2010). This process, while necessary for effective action, comes at a cost: it progressively "decoheres" the cognitive system, locking it into a set of increasingly rigid, high-certainty interpretations. The synaptic weights and neural assemblies that encode these interpretations become strongly reinforced, potentially at the expense of alternative configurations (Yang et al., 2014). This is the brain’s "which-path record," etched into its connectivity.

Sleep initiates the erasure of this record. Crucially, this is not an erasure of memory content, but of the certainty or precision-weighting attached to specific causal interpretations. The mechanism operates through a multi-pronged neurobiological strategy that mirrors the logic of the quantum eraser:

- **Sensory Disconnection**: The thalamus gates sensory input to the cortex, dramatically attenuating the stream of external evidence that normally sustains and validates waking interpretations (McCormick & Bal, 1997). This disconnection is the first and most critical step, equivalent to isolating the quantum system from its which-path measuring apparatus. Without a constant influx of confirming sensory data, the evidential support for the dominant waking models begins to fade.
- **Neuromodulatory Reversal**: The sleep cycle is characterized by a radical shift in neuromodulatory tone. Levels of norepinephrine and serotonin, neuromodulators associated with focused attention, environmental engagement, and the precision-weighting of prediction errors, drop to their lowest levels during slow-wave

sleep (SWS) (Pace-Schott & Hobson, 2002). This global reduction in neuromodulatory "gain" effectively lowers the precision afforded to all top-down predictions and bottom-up errors, softening the sharp distinctions between competing models. The cholinergic dominance during REM sleep further promotes a hyper-associative, internally generated state that is poorly constrained by external reality (Hobson & Friston, 2012).

## Weakening Environmental Support and Reducing Free Energy Gradients

The waking environment provides continuous, high-precision support for the brain's localized interpretations. Sleep suspends this support. In the absence of this external "scaffolding," the free energy landscape—a mathematical formulation of the brain's surprisal—undergoes a profound transformation (Hobson & Friston, 2016).

During wakefulness, the free energy landscape is steep and rugged, with deep, narrow valleys corresponding to the brain's high-certainty interpretations. The difference in free energy (ΔF) between the dominant model (the deepest valley) and its alternatives is large, making a transition (a change of mind) energetically costly. Sleep, through sensory disconnection and neuromodulatory changes, flattens this landscape. It reduces the ΔF between models by selectively downscaling synaptic strengths that were heavily engaged during wakefulness, a process central to the Synaptic Homeostasis Hypothesis (SHY) (Tononi & Cirelli, 2006). This global synaptic downsconing lowers the energetic "barrier" between competing hypotheses, making the system more labile. The brain is no longer trapped in the deep valleys of its waking convictions.

## The Restoration of Permissible Interference

With the which-path information degraded and the free energy landscape flattened, the conditions for cognitive interference are reinstated. This is not the directed interference of focused thought, but a spontaneous, system-wide recombination. The hallmark electrophysiological signatures of sleep reflect this state:

- **Slow-Wave Oscillations (SWOs)**: The slow (<1 Hz), high-amplitude oscillations of SWS are thought to orchestrate the reactivation and redistribution of memory traces. These waves facilitate a dialogue between the hippocampus and neocortex, but crucially, they do so in a temporally compressed, off-line manner (Diekelmann & Born, 2010). This replay is not a faithful reiteration of a single path; evidence suggests it involves the selective strengthening of some traces and the weakening of others, and can include novel sequences that never occurred in waking experience (Lewis & Durrant, 2011). This is interference in action: the superposition and recombination of memory elements.
- **REM Sleep and Theta-Gamma Coupling**: The theta rhythms (4-8 Hz) dominant in REM sleep, often coupled with gamma bursts, create a neurophysiological environment ideal for associative linking. This state is characterized by high cholinergic activity and resembles a "virtual reality generator," where memories, emotions, and concepts are interwoven without the constraints of logic or sensorimotor coherence (Nielsen, 2000). This chaotic, interference-rich process may be essential for emotional memory processing and creative integration (Walker & van der Helm, 2009).

### Sleep as a Necessity for De-Localization

Therefore, sleep is not primarily for creating new data, but for allowing the brain's existing data structures to stop being localized. It is the brain's intrinsic quantum eraser. By periodically erasing the precision-weighted "which-path" record of wakefulness, sleep prevents the cognitive system from becoming irreversibly trapped in the deep valleys of its own past inferences. It restores the system's entropy or potential energy, enabling the interference of hypotheses that is the wellspring of memory flexibility, creative insight, and adaptive behavior (Lewis et al., 2018). A failure of this erasure mechanism—where the brain cannot sufficiently decouple from its waking certainties—may manifest as the rigid, over-precise thinking seen in conditions like anxiety, addiction, or traumatic re-experiencing (Sterzer et al., 2018). In this light, the nightly journey into sleep is not an escape from reality, but a vital computational reset, ensuring that each new day begins not with a fixed, decohered past, but with a brain capable of once again navigating the superposed possibilities of the future.

# Two Generative Models of the Brain: The Ze Duality

The coherence of classical wave interference depends on the indistinguishability of paths; in the cognitive domain, this translates to the brain's ability to entertain multiple interpretations simultaneously. To explain how this dynamic unfolds, the Ze framework proposes that the brain's architecture is fundamentally organized around at least two core, competing generative models. This duality is not merely functional but reflects a deep computational schism between the imperative for immediate action and the capacity for reflective understanding. These models—termed here the Forward Model (Model A) and the Inverse Model (Model B)—continuously generate and evaluate predictions about the world. Cognitive interference, the hallmark of the double-slit mode, is the computational state that arises when their outputs can be reconciled without a definitive commitment to a single "path." The tension and interaction between these models form the substrate of conscious experience, from fluid perception to paralytic indecision (Cisek & Kalaska, 2010; Buckner & Carroll, 2007).

### Model A: The Forward, Sensorimotor Model of Action

Model A is pragmatic, embodied, and directed toward the future. Its primary function is to navigate the present moment by predicting the sensory consequences of potential actions and selecting those that minimize expected free energy or surprise (Friston et al., 2016). This model is fundamentally *causal* and *prospective*.

- **Neuroanatomical and Functional Correlates**: Model A is closely associated with the dorsal visual stream (the "where/how" pathway) and frontoparietal action-observation networks (Milner & Goodale, 2008). It relies on fast, subcortical circuits involving the basal ganglia for action selection and the cerebellum for refining predictive motor control (Wolpert et al., 1998). Its computations are often described in terms of active inference, where action is conceived as a way to sample sensory data that confirms the agent's predictions about being in a preferred state (Friston, 2010).

- **Computational Mandate**: Model A answers questions like "What can I do?" and "What will happen if I do that?" It operates with high temporal resolution but relatively coarse semantic detail, prioritizing spatial location, affordances, and motor feasibility (Clark, 2013). Its success metric is survival and goal attainment in the immediate sensorimotor context. Model A is the primary consumer of "which-path" information; it demands localization to execute a specific, unambiguous motor command. Its functioning is dominant during states of focused task engagement, threat response, and skilled performance (Aston-Jones & Cohen, 2005).

## Model B: The Inverse, Reconstructive Model of Understanding

In contrast, Model B is reflective, reconstructive, and oriented toward explanation. Its primary function is to infer the most likely *causes* of sensory data, constructing coherent narratives about the past, the internal state of others, and counterfactual possibilities (Hassabis & Maguire, 2009). This model is fundamentally *diagnostic* and often *retrospective* or *counterfactual*.

- **Neuroanatomical and Functional Correlates**: Model B is largely associated with the default mode network (DMN), including the medial prefrontal cortex, posterior cingulate cortex, and angular gyrus (Raichle, 2015). It also heavily engages the ventral visual stream (the "what" pathway) for object identification and the hippocampal formation for episodic memory and scene construction (Buckner & Carroll, 2007). Its operations are slower, more energy-intensive, and involve deep semantic and contextual processing.
- **Computational Mandate**: Model B answers questions like "What caused this?" "What does this mean?" and "What could have happened?" It seeks to build a stable, consistent model of the world that explains events in terms of hidden causes, intentions, and abstract relationships (Hohwy, 2016). It is less concerned with immediate action and more with long-term understanding and social cognition. Model B can tolerate ambiguity and hold multiple conflicting interpretations in parallel, as it explores different causal stories. It is predominant during mind-wandering, reminiscence, planning beyond the immediate future, and social reasoning (Spreng et al., 2009).

## Interference at the Model Interface: The Double-Slit Condition

The Ze framework posits that the characteristic "interference pattern" of higher cognition arises precisely at the interface where the predictions and inferences of Model A and Model B must be integrated. For most routine perceptions and actions, the models are aligned: seeing a cup (Model B) seamlessly affords reaching for it (Model A). However, in situations of novelty, ambiguity, or conflict, their outputs diverge.

Cognitive interference is possible when sensory data is sufficiently ambiguous to be accommodated by *both* models without forcing one to cede dominance. For instance, an ambiguous social cue might be interpreted by Model B as either friendly or hostile, while Model A generates corresponding approach or avoidance motor schemata. As long as no decisive "which-path" information (e.g., a clarifying word, a definitive action) is introduced, the brain can maintain this superposition of "friend/approach" and "foe/avoid" interpretations. This state is subjectively experienced as uncertainty, contemplation, or imaginative brainstorming (Müller et al., 2021). Neurophysiologically, it may be reflected in sustained, competing activity in the neural substrates of both models without a clear winner-take-all resolution (Sterzer et al., 2009).

## Localization as Model Resolution

Localization occurs when the conflict at the interface must be resolved. This is typically forced by one of two mechanisms:

1. **The Imperative of Action**: Model A, with its mandate for decisive behavior, can force a collapse. The need to act—even if randomly—provides overwhelming "which-path" information through proprioceptive feedback, committing the system to one motor plan and its associated perceptual interpretation (Cisek & Kalaska, 2010).
2. **The Triumph of Narrative**: Model B can also force localization if one causal narrative becomes overwhelmingly more coherent or parsimonious, dramatically lowering its free energy compared to alternatives. A sudden insight or "Aha!" moment represents this kind of rapid, narrative-driven collapse (Jung-Beeman et al., 2004).

The process of resolution often involves the anterior cingulate cortex (ACC), which monitors conflict between competing representations, and the dorsolateral prefrontal cortex (dlPFC), which implements cognitive control to suppress the losing model and amplify the winner (Botvinick et al., 2004).

## Implications for Psychopathology and Creativity

This duality framework sheds light on mental disorders. Conditions like anxiety and obsessive-compulsive disorder may reflect a dysfunctional stalemate where Model B generates catastrophic counterfactuals that Model A cannot resolve through action, leading to persistent, paralytic interference (Paulus & Stein, 2006). Conversely, psychosis may involve a pathological dominance of Model B’s internal narratives, which become so precise and compelling that they override the "which-path" information provided by external sensory evidence (Model A), leading to fixed, delusional localization (Corlett et al., 2019).

Conversely, creativity can be seen as the optimized management of this interference. It requires the suppression of Model A’s demand for immediate, pragmatic localization, allowing Model B to freely recombine concepts and generate novel counterfactuals (the interference phase), followed by a controlled localization where a valuable new combination is selected and enacted (Beaty et al., 2016).

## The Interfering Dyad

The brain, therefore, is not a unified inference machine but a dyad of competing inferential systems. The Forward Model (A) and the Inverse Model (B) are in constant dialogue, their agreement yielding decisive thought and action, their disagreement generating the rich interference patterns of contemplation, doubt, and imagination. The double-slit experiment is happening in the brain because its very architecture is built upon this fundamental duality. Sleep, as previously argued, acts as a regular eraser of the path commitments forced by this daily conflict, resetting the interference potential between these two great generative models of our existence.

# Localization as a Forced Process

In the quantum double-slit experiment, the transition from an interference pattern to localized particle impacts is often misinterpreted as requiring a conscious observer or an act of measurement that "chooses" a reality. Modern decoherence theory demonstrates this is not the case; localization is a forced, physical outcome of the system's interaction with its environment (Zurek, 2003). Similarly, the Ze framework posits that cognitive localization—the collapse of competing hypotheses into a single, actionable interpretation—is not a voluntary act of will, a conscious choice, or dependent on an internal homunculus observer. Instead, it is an inevitable, subpersonal computational outcome forced upon the brain’s generative models when specific thermodynamic and pragmatic conditions are met (Friston, 2010). This process is governed by the mathematics of variational free energy minimization and emerges directly from the brain’s embeddedness in a sensorimotor environment.

## Demystifying Localization: Beyond Will and Conscious Choice

The intuitive notion that we "choose" what to perceive or "decide" what something means places the cart before the horse. A wealth of neuroscientific evidence suggests that the resolution of perceptual ambiguity often occurs pre-consciously, with conscious awareness registering the outcome of localization, not its process (Dehaene et al., 2006). In binocular rivalry, for instance, perceptual switches between competing images happen spontaneously and automatically, even when observers are instructed to hold one percept (Meng & Tong, 2004). Similarly, the "Aha!" moment of insight feels like a sudden gift, not a deliberative choice, suggesting the underlying computation reaches a threshold outside of direct conscious control (Jung-Beeman et al., 2004).

Cognitive localization, therefore, is better understood as a transition in the state of a dynamical system. It is akin to the phase transition of water freezing at 0°C; the properties of the system change dramatically when a critical parameter threshold is crossed, without any external "choice" being made. In the brain, this parameter is the difference in variational free energy ($\Delta F$) between competing generative models (Hohwy, 2016).

## The Free Energy Threshold: A Thermodynamic Imperative

Under the free energy principle, the brain’s fundamental imperative is to minimize surprise (or variational free energy, a bound on surprise) by refining its internal models to better predict sensory inputs (Friston, 2010). In a state of cognitive interference, multiple models have comparable free energy values, meaning they are roughly equally good at explaining the available data. The system remains in a superpositional state.

Localization is forced when this balance is catastrophically broken. This occurs when one model, through the accrual of new sensory evidence or internal computation, achieves a significantly lower free energy than its rivals. The $\Delta F$ between the leading model and the alternatives exceeds a stability threshold inherent to the neural architecture (perhaps related to synaptic efficacy or neuromodulatory gain). This creates a steep free energy gradient, making the current state (maintaining interference) metabolically and computationally unsustainable. The system is compelled to move down the gradient, transitioning to the state of lowest free energy—the localized interpretation. This is not a choice but a physical and computational necessity, analogous to a ball rolling into the deepest valley on a landscape (Friston & Kiebel, 2009).

## Environmental Support as a Driving Force

The environment is not a passive backdrop but an active participant in forcing localization. The "which-path" information provided by the environment (Part 3) directly shapes the free energy landscape. When the sensory milieu unambiguously supports one interpretation—a clear visual form, a coherent sentence, a consistent social cue—it provides high-precision prediction errors that can only be explained away (minimized) by one specific generative model (Feldman & Friston, 2010). This selective increase in the precision (inverse variance) of sensory data for one path dramatically lowers its associated free energy.

The forced nature of this is evident in phenomena like the "pop-out" effect in visual perception, where a salient stimulus automatically captures attention and perception, irrespective of top-down goals (Theeuwes, 2010). The environment, through the statistical structure of the sensory input, forces a specific localization. This mirrors quantum decoherence, where interaction with environmental degrees of freedom (e.g., scattered photons) carries away which-path information, forcing the system into a localized state relative to that environment (Schlosshauer, 2007).

## Action as the Ultimate Enforcement Mechanism

The most potent catalyst for forced localization is the imperative for action. Model A, the forward sensorimotor model (Part 5), has a low tolerance for superposition. To execute a coherent motor command, the brain must commit to a specific model of the body and its relationship to objects in the world (Cisek & Kalaska, 2010). The initiation of an action, or even its preparation, constitutes a profound form of self-measurement.

When an action becomes inevitable—whether due to a looming threat, a time constraint, or a pre-potent habit—it generates a cascade of proprioceptive predictions. These predictions can only be fulfilled if the sensory feedback matches a specific anticipated state of the world. This creates an overwhelming influx of expected precision-weighted prediction errors that align exclusively with one causal interpretation. To avoid catastrophic prediction error, the brain must instantiate the model that predicts the sensory consequences of that specific action, thereby localizing perception to fit the act (Friston et al., 2016). This is demonstrated in "action-forced" perceptual decisions, where the mere requirement to make a speedy motor response accelerates perceptual stabilization (Gallagher et al., 2013).

### The Analogy to Molecular Localization

The forced localization of a molecule in a double-slit experiment provides a precise physical analogy. The molecule does not "choose" a slit. Its wavefunction interacts with the slits and the surrounding environment (air molecules, thermal radiation, etc.). If the experiment is performed in a way that allows which-path information to be encoded in the environment (a process called einselection), decoherence occurs on a timescale determined by the strength of that interaction (Zurek, 2003). Localization is forced when the system-environment entanglement becomes irreversible for all practical purposes. The "choice" of slit is determined by the specific configuration of the interaction, not by a ghost in the machine.

Similarly, cognitive localization is forced when the interaction between the brain's generative models and its sensorimotor environment creates an irreversible commitment. The specific "choice" of interpretation is determined by the configuration of sensory evidence, synaptic weights, bodily states, and pragmatic demands at that moment. The feeling of conscious will may arise from the proprioceptive and metacognitive sensations associated with this forced transition, creating a post-hoc narrative of agency (Haggard, 2008), but it is not the cause.

### From Metaphysics to Mechanics

Viewing cognitive localization as a forced process moves the discussion from the realm of metaphysics to that of computational neurobiology. It dissolves the need for a mysterious observer in both quantum physics and cognitive science. The brain, like the quantum system in a double-slit apparatus, localizes when it must—when free energy differentials become too great, when environmental support becomes too lopsided, and when action becomes the only viable path to minimize surprise. Understanding the triggers and thresholds of this forced collapse is crucial for explaining not only normal perception and decision-making but also its pathologies, where the process may become too rigid (as in delusion) or too unstable (as in psychosis). The experiment is not a thought experiment; it is a continuous, forced reality of a brain engaged in the struggle to exist within its world.

## Structural Isomorphism: Why Molecules and the Brain Are Not a Metaphor

The claim that cognitive processes are "like" the double-slit experiment often remains at the level of analogy. The Ze framework, however, posits a stronger, more formal relationship: a structural isomorphism. This isomorphism exists because both complex quantum systems (like large molecules used in interference experiments) and the brain share fundamental architectural and dynamic properties that necessitate an interference-to-localization workflow. They are not similar by chance but because they are both adaptive, self-organizing systems navigating uncertainty within a larger environment. Recognizing this isomorphism elevates the comparison from a poetic metaphor to a principled theoretical bridge between quantum physics and cognitive neuroscience (Bruza et al., 2015; Atmanspacher & beim Graben, 2009).

## Molecules with Internal Degrees of Freedom: The Proto-Cognitive System

The iconic double-slit experiment is often imagined with elementary particles like electrons or photons. However, groundbreaking experiments have demonstrated quantum interference with increasingly complex objects, including fullerenes ($C_{60}$), large organic molecules, and even synthetic molecules with over 2000 atoms (Arndt et al., 1999; Fein et al., 2019). These are not structureless points; they possess rich internal degrees of freedom (iDOFs)—vibrational, rotational, and electronic states. This is the first key to the isomorphism.

During interference, these iDOFs can become entangled with the molecule's center-of-mass position (the "which-path" degree of freedom). For instance, a photon scattered from the molecule as it passes a slit could carry away information, correlating the molecule's internal state with its path. This entanglement is the physical basis for decoherence (Zurek, 2003). The molecule, by virtue of its own complex internal structure, acts as a rudimentary "measurement device" on itself. It is not a passive particle but a system whose parts interact and exchange information, creating a primitive form of internal "environment" that can record which-path information (Hornberger et al., 2012). This self-interaction foreshadows the brain's recursive architecture.

## The Brain's Recursive Architecture: A Labyrinth of Its Own Making

The mammalian brain is the epitome of a system with hierarchical, recursive internal structure. Its connectivity is not feedforward but dominated by massive feedback and recurrent loops. Higher-order cortical areas send as many, if not more, projections back to lower areas as they receive, creating continuous cycles of prediction and prediction-error signaling (Friston, 2010). This means that every "part" of the brain is simultaneously a processor and an environment for other parts.

For example, activity in the prefrontal cortex (associated with high-level models and goals) provides a contextual "environment" that shapes processing in sensory cortices via top-down predictions. Simultaneously, the resulting sensory activity updates the prefrontal model. This creates a recursive, self-referential loop where the brain's own higher-order states continuously "measure" and constrain its lower-order states, and vice versa (Hohwy, 2016). This internal ecosystem is vastly more complex than a molecule's iDOFs, but it serves an isomorphic function: it provides a rich internal medium for encoding, circulating, and potentially erasing "which-path" information about cognitive states.

## Self-Decohierence: From Fast Molecular Collapse to Cognitive Acceleration

Large molecules in interference experiments are notoriously fragile. They rapidly self-decohere because their own internal thermal vibrations and interactions with their internal electromagnetic fields act as a built-in source of environmental coupling (Hackermüller et al., 2004). This is why such experiments require extreme vacuum and cryogenic conditions—to shield the molecule from external decoherence long enough for the more insidious self-decoherence to become the limiting factor. The molecule's own complexity accelerates its transition from quantum interference to classical localization.

The brain exhibits a precisely analogous, but actively regulated, capability for cognitive self-decoherence. During wakefulness, the brain does not passively await environmental measurement; it actively accelerates its own localization. It does this through neuromodulatory systems (e.g., noradrenergic and cholinergic projections) that regulate the precision or gain of neural computations (Feldman & Friston, 2010). By increasing the precision-weighting of specific prediction errors—say, those confirming a particular hypothesis—the brain effectively amplifies the "signal" from certain internal models, increasing the conflict ($\Delta F$) with others and forcing a rapid, winner-take-all resolution. This is an active, metabolic process of enhancing internal signal-to-noise to expedite cognitive collapse, mirroring how a molecule's internal heat catalyzes its own decoherence (Aston-Jones & Cohen, 2005).

## The Brain as Its Own Environment: The Closure of the Perception-Action Loop

The most profound isomorphism lies in operational closure. A molecule in a vacuum chamber is, to a first approximation, an isolated object. The brain, however, achieves a functional closure through the perception-action cycle (Friston et al., 2016). The brain is not merely inside an environment; it enacts its environment through action. Its motor actions change sensory input, which updates its models, which guide new actions.

This means the brain's primary "environment" for the purposes of cognitive localization is its own sensorimotor embodiment. The reafferent sensory feedback from a committed action is the most potent "which-path" information possible, as it is perfectly correlated with the motor command that generated it. In this closed loop, the brain is both the experimenter (generating actions) and the measuring apparatus (sensing the consequences). It is its own double-slit apparatus, its own source of decohering interaction (Clark, 2013). This operational closure creates a stable, self-consisting world in which cognitive localization is not just possible but necessary for coherent behavior.

5. From Prototype to Process: A Unifying Computational Principle

Therefore, large interfering molecules are not merely metaphors for the brain; they are physical prototypes that illuminate a universal computational principle. The principle is this: any sufficiently complex, self-interacting system that must infer hidden states from sparse data will exhibit a dynamic trade-off between maintaining a superposition of plausible states (interference) and committing to one state (localization) to minimize a quantity like free energy. The molecule does this through the physics of entanglement and decoherence across its iDOFs. The brain does this through the neurocomputational dynamics of predictive coding and precision-weighting across its hierarchical, recurrent networks (Friston & Kiebel, 2009).

The parameters differ—vibrational modes versus neural assemblies, scattering photons versus neuro-modulatory signals—but the formal, mathematical structure of the problem is conserved. This isomorphism explains why concepts from quantum theory, such as superposition, non-commutativity, and contextuality, have found fertile ground in formal models of decision-making and conceptual reasoning (Busemeyer & Bruza, 2012; Pothos & Busemeyer, 2022).

### A Bridge Across Scales

Recognizing this structural isomorphism dismantles the artificial wall between the "quantum" and the "classical" brain. It suggests that the phenomenon observed in the double-slit experiment is not a quirky property of the very small, but a fundamental organizational motif for complex, inferential systems. The molecule shows the principle in its most elementary physical form. The brain instantiates it in its most spectacularly complex biological form, adding layers of regulation, memory, and meta-control. In both, localization is a forced process arising from the system's own structure interacting with itself and its world. The experiment is not just happening in the brain; the brain is a sophisticated, evolved embodiment of the very physics the experiment reveals.

## Psychopathology as a Dysregulation of the Which-Path / Eraser Mechanism

The Ze framework proposes that healthy cognition depends on a dynamic equilibrium between the generation of cognitive "which-path" information (forcing localization for action) and its periodic "erasure" during states like sleep (restoring interference for flexibility). This regulatory cycle mirrors the controlled conditions of a quantum experiment. Psychopathology, then, can be reformulated not merely as a chemical imbalance or faulty wiring, but as a fundamental dysregulation of this core cognitive quantum dynamic (Friston et al., 2014). Specifically, symptoms across diagnostic categories can be understood as manifestations of either a failure to adequately generate or maintain which-path information (leading to excessive, chaotic interference) or a failure to effectively erase it (leading to pathological, rigid hyper-localization). The blurring of boundaries between states like sleep and wakefulness, a common transdiagnostic feature, becomes a key phenomenological clue to this underlying computational failure.

### Excessive Erasure and Pathological Interference: The World Without a Path

In the healthy brain, the "quantum eraser" function of sleep is temporally bounded and reversible. In certain conditions, however, a similar erasure of which-path information appears to operate inappropriately during waking consciousness, or the brain fails to generate sufficient which-path information altogether. This results in a state of chronic, debilitating cognitive interference where hypotheses cannot be stabilized.

- **Psychosis and Schizophrenia**: The positive symptoms of psychosis—hallucinations and delusions—can be interpreted through this lens. According to predictive coding theories, psychosis may arise from an abnormal weakening of the precision-weighting afforded to sensory evidence (bottom-up prediction errors) relative to internal prior beliefs (top-down predictions) (Sterzer et al., 2018; Corlett et al., 2019). In Ze terms, this is a failure of sensory "which-path" information. The external world's constraints are effectively "erased" or rendered too imprecise to force localization. Consequently, the brain's internal generative models (particularly the inverse, narrative Model B) operate in a high-interference state, freely combining memories, fears, and concepts without being pinned down by sensory reality. A hallucination is a localized percept born from this uncontrolled interference, while a delusion is a hyper-localized narrative that emerges as a desperate, fixed attempt to explain the resulting chaotic internal experience (Fletcher & Frith, 2009).

- **Dissociative Disorders**: Dissociation, characterized by feelings of detachment from reality, self, or memories, represents a more global failure of which-path integration. Here, the "path" that is erased or destabilized is the integrative narrative of selfhood and autobiographical continuity. Traumatic stress can disrupt the normal hierarchical integration of sensory, emotional, and narrative information, preventing the formation of a coherent, localized self-model (Lanius et al., 2010). The result is a fragmentation of consciousness—a persistent interference pattern between disparate self-states or between the self and the body, experienced as depersonalization or derealization.

## Pathological Fixation and Failed Erasure: The Single, Inescapable Path

The opposite dysregulation occurs when the brain becomes trapped in a single, over-precise interpretation, unable to engage the "eraser" mechanisms that would allow for de-localization and reconfiguration. The which-path information is not just strong; it is absolute and impervious to revision.

- **Post-Traumatic Stress Disorder (PTSD) and Intrusive Memories**: PTSD can be viewed as a catastrophic failure of the cognitive quantum eraser, specifically for episodic memory. A traumatic event creates an overwhelmingly precise and salient memory trace—an ultra-strong "which-path" record ("this is exactly what happened"). Normally, sleep-dependent memory replay and synaptic downscaling (Tononi & Cirelli, 2014) would integrate and soften this memory, reducing its precision and emotional salience by allowing it to interfere with other related memories. In PTSD, this erasure/integration process fails. The traumatic memory remains hyper-localized, isolated, and intrusively re-experienced with high perceptual and affective precision, as if the event were continually being "measured" anew (Brewin, 2015). The boundary between past (memory) and present (perception) collapses because the path cannot be erased.
- **Major Depressive Disorder and Cognitive Rigidity**: A core feature of depression is cognitive inflexibility—a persistent, negative interpretation of self, world, and future (the "cognitive triad"). In Ze terms, this is a state of hyper-localization onto a catastrophic narrative model (Model B). The brain’s neurochemical state in depression, including altered monoamine and glutamatergic function, may create a global increase in the precision of negative prior beliefs, making them resistant to disconfirming evidence (which-path information from positive experiences) (Roiser et al., 2012). Furthermore, the sleep architecture in depression is often fragmented, with reduced slow-wave sleep (the primary "eraser" stage), potentially impairing the nightly reset that would allow for a reorganization of these rigid cognitive patterns (Riemann et al., 2020). The depressive mind is thus stuck on a single, negative path.

- **Obsessive-Compulsive Disorder (OCD)**: OCD presents a compelling hybrid. An intrusive thought or image (an unwanted, interference-born hypothesis) breaks into awareness. The brain then attempts to force a pathological localization through compulsive action or mental ritual. The compulsion is a maladaptive, self-generated "which-path" measurement—an action designed to create sensory feedback that temporarily confirms a specific, safe state and collapses the anxiety-provoking uncertainty (Robbins et al., 2019). However, this localization is transient and fragile, requiring constant repetition, indicating a deeper failure in the regulatory mechanism that normally maintains adaptive confidence in perceptual-motor inferences.

### The Blurred Boundary: A Hallmark of Dysregulation

The phenomenological blurring of sleep-wake boundaries in many disorders—such as vivid, nightmare-ridden sleep in PTSD, hypnagogic/hypnopompic hallucinations in psychosis, or excessive daytime sleepiness in depression—is not a mere side effect. It is a direct symptom of the core computational dysregulation. It indicates that the distinct neurophysiological states required for controlled localization (wake) and controlled erasure/interference (sleep) are no longer properly segregated or regulated (Muto et al., 2012). The "experimental apparatus" of the mind is leaking, allowing the processes of one state to intrude upon the other.

### A New Taxonomy of Cognitive Dynamics

The Ze framework suggests a transdiagnostic, process-based taxonomy of mental disorders centered on the regulation of cognitive interference and localization. This moves beyond descriptive symptom clusters to underlying computational failures: Is the system suffering from Too Much Interference (a deficit of which-path information, as in psychosis and dissociation) or Too Much Localization (a deficit of erasure, as in PTSD, depression, and aspects of OCD)? This view has direct implications for treatment. Therapies may aim to either strengthen which-path information (e.g., reality testing in CBT for psychosis, grounding techniques in dissociation) or enhance erasure/flexibility (e.g., EMDR for PTSD, sleep hygiene and therapies targeting cognitive flexibility in depression). By framing the brain as a self-experimenting quantum system, we gain a powerful new lexicon to describe its most profound breakdowns.

# Coma, Anesthesia, and Psychedelics as Distinct Ze Regimes

If the healthy waking brain operates in a dynamic balance between interference and localization, then altered states of consciousness can be understood as specific perturbations of this equilibrium. The Ze framework provides a unifying computational lens through which to view otherwise disparate phenomena: coma, general anesthesia, and the psychedelic state. These are not merely "altered states" but distinct, experimentally accessible regimes of the brain's double-slit dynamics, each characterized by a specific configuration in the competition and interaction between the Forward (Model A) and Inverse (Model B) generative models (Bayne et al., 2020). By analyzing these states, we move from analogy to experimental prediction, grounding the theory in observable neurophysiological and phenomenological outcomes.

 

## Coma: The Suspension of Active Inference

Coma represents the most profound departure from the waking interference-localization cycle. It is defined by a complete loss of wakefulness and awareness, with no signs of sleep-wake cycling (Laureys, 2005). In the Ze framework, coma is interpreted as a global suppression of both generative models. The machinery of active inference—the continuous process of minimizing free energy through perception and action—is severely disrupted or halted.

Neurophysiologically, coma is often associated with widespread cortical deafferentation (due to brainstem or thalamic injury) or diffuse bilateral cortical damage (Schnakers & Monti, 2017). This disrupts the thalamocortical loops essential for generating and sustaining the large-scale integrated activity patterns that underpin conscious models of the world (Alkire et al., 2008). The result is not a shift in the balance between Models A and B, but a collapse of the platform upon which their conflict generates experience. There is no "which-path" information to process, no interference pattern to resolve, and no capacity for localization. The cognitive double-slit experiment is not running; the apparatus is powered down. Recovery from coma often involves the gradual re-emergence of this dynamic, beginning with the most primitive sensorimotor loops (Model A precursors) before more complex, narrative functions (Model B) return (Gosseries et al., 2014).

## General Anesthesia: Artificial Localization Without Interpretation

General anesthesia (GA) induces a reversible state of unconsciousness, amnesia, and immobility. Unlike coma, it is a pharmacologically controlled perturbation. The Ze framework proposes that a primary mechanism of GA is the induction of a widespread, artificial cognitive localization that preempts meaningful interpretation. It forces the system into a stable, low-complexity state that is incompatible with conscious inference.

This can be understood through the concept of network integration. Conscious processing is associated with a rich, differentiated, and integrated pattern of activity across the brain's functional networks (Tononi, 2008). Psychedelics, as discussed next, increase integration but also differentiation. In contrast, many anesthetic agents, particularly propofol and sevoflurane, appear to disrupt integration while potentially increasing functional homogeneity. They enhance low-frequency, high-amplitude oscillations (like delta waves) and suppress the higher-frequency gamma activity associated with precise, localized cortical computation (Brown et al., 2010). Furthermore, they disrupt the connectivity of key hubs like the posterior cingulate cortex/precuneus, a central node of the default mode network (Model B) (Pal et al., 2020).

In Ze terms, anesthesia does not erase which-path information; it saturates the system with a uniform, noisy signal (or suppresses signal transmission) so that no specific "path" can be meaningfully distinguished or selected. It imposes a pharmacologic "decoherence" that is so complete it prevents the formation of any coherent interference pattern in the first place. The brain is localized into a single, uninformative state—a steady "hum" that carries no model of the world. This is why awakening from GA feels like an abrupt jump from non-existence back into the stream of consciousness, with no memory of the intervening "measurement."

## Psychedelics: Enhancement of Interference via Which-Path Attenuation

The psychedelic state, induced by classic serotonergic agonists like psilocybin or LSD, presents a mirror image of anesthesia. Instead of suppressing models, it profoundly alters their interaction by attenuating "which-path" information and thereby amplifying cognitive interference. The primary phenomenological reports—increased sensory vividness, loosening of ego boundaries, enhanced imagination, and the blending of senses and concepts—are hallmarks of a brain in a high-interference, poorly localized state (Carhart-Harris et al., 2014).

Neurophysiologically, this is supported by key findings:

- **Reduced Precision of Priors**: Under the relaxed beliefs/potentiated priors model of psychedelics, these compounds are thought to flatten the brain's hierarchical predictive landscape by reducing the precision-weighting of high-level, longstanding prior beliefs (Carhart-Harris & Friston, 2019). In Ze terms, this is a chemical "erasure" of the learned which-path information embedded in Model B's narrative structures (e.g., the ego, categorical boundaries). With these constraints weakened, a much wider space of interpretations becomes probabilistically viable.
- **Increased Entropy and Integration**: Brain imaging shows that psychedelics increase the entropy (randomness) of cortical activity while paradoxically increasing global functional connectivity (Tagliazucchi et al., 2014). This describes a system where many more neural states are active (high interference) and communicating freely across traditional modular boundaries. The strict, efficient coding of the waking state breaks down.
- **Disintegration of the Default Mode Network (DMN)**: Psychedelics consistently reduce activity and integrity within the DMN, the core substrate of Model B (Carhart-Harris et al., 2012). This directly weakens the narrative, self-referential model, allowing sensory (Model A) and emotional processes to intermix with it more freely, creating novel, interference-born percepts and thoughts.

The subject experiences a flood of superimposed possibilities—synaesthesia, autobiographical memories merging with present perception, fluid morphing of visual forms. This is the cognitive interference pattern made conscious. The "experiment" is running, but the "which-path" detectors (the precise priors of the DMN) have been disabled. Localization becomes difficult or transient.

## A Spectrum of Cognitive Regimes

Coma, anesthesia, and psychedelics thus delineate a spectrum of the brain's operational regimes within the Ze framework. They demonstrate that consciousness is not a binary on/off switch but a specific mode of dynamic instability between competing models. We can suppress the models entirely (coma), force a global localization that voids content (anesthesia), or dissolve the constraints that normally force localization, unleashing interference (psychedelics). Each state provides a crucial experimental window: coma shows the substrate of the dynamic, anesthesia shows the effect of forcing a null state, and psychedelics show the raw potential of unleashed interference. Together, they validate the core premise that the brain's normal function is a carefully managed version of the very same quantum-style computation that these interventions push to its extremes. Understanding these regimes not only clarifies states of altered consciousness but also sharpens our understanding of the fragile, beautiful interference pattern we call normal wakeful awareness.

# Against Copenhagen: Locality Without an Observer

The Copenhagen interpretation of quantum mechanics, for all its historical importance, introduced a persistent and problematic dualism: it posited that the act of observation by a conscious observer is necessary to collapse the wavefunction, transforming possibility into actuality (Heisenberg, 1958). This view has seeped into popular consciousness and, at times, into speculative theories of mind, suggesting that consciousness itself might be a fundamental force in physics. The Ze framework, grounded in active inference and modern decoherence theory, forcefully rejects this notion. It argues that in both the quantum experiment and the brain's cognitive processes, localization (or collapse) is a physical, subpersonal, and observer-independent process (Zurek, 2003). It arises as a mechanical consequence of a system minimizing variational free energy through interaction with its environment, not as a mystical result of being seen, measured, or consciously registered (Friston, 2010).

## Decoherence: The Observer-Free Collapse

The Copenhagen interpretation's need for an observer has been largely supplanted by the theory of decoherence. Decoherence demonstrates how the interaction of a quantum system with its environment—through the scattering of photons, collisions with air molecules, or entanglement with internal degrees of freedom—irreversibly leaks "which-path" information into the environmental degrees of freedom (Schlosshauer, 2007). This process, einselection, destroys quantum coherence and leads to the emergence of classical, localized properties without any human observer or conscious act. The environment itself acts as a continuous, physical measurement device. As Zurek (2003) established, decoherence solves the "preferred basis problem," showing why we perceive definite positions and not, say, definite superpositions of momentum and position. The transition from quantum to classical is driven by thermodynamic openness and interaction, not by subjective awareness.

## The Brain as a Self-Decohiring System: No Internal Homunculus

If we accept that quantum systems localize via environmental interaction, the Ze framework's claim gains its force: the brain is a physical system that performs an isomorphic computation. Cognitive localization—the stabilization of one perceptual hypothesis or decision—is the brain's version of decoherence. Here, the "environment" with which the brain's generative models interact is twofold: the external sensorimotor world and, crucially, the brain's own internal, hierarchical structure.

As argued previously, "which-path" information in the brain is supplied by precision-weighted sensory data, motor reafference, and social cues. When this information reaches a critical threshold of precision, it forces a resolution in the competition between internal models (Feldman & Friston, 2010). This happens through well-understood neurophysiological winner-take-all dynamics, such as inhibitory competition between neural assemblies and synchronization of the winning coalition (Engel & Singer, 2001). At no point is an internal "little man" or conscious self required to "look" at the options and choose. The process is subpersonal and automatic. Evidence from priming and subliminal perception studies shows that stimuli can be fully processed, influencing behavior and even high-level decisions, without ever reaching conscious awareness—localization and guidance of action occur entirely in the absence of conscious observation (Dehaene et al., 2006).

## Consciousness as a Consequence, Not a Cause

The Ze framework inverts the Copenhagen-inspired view. It does not posit consciousness as a cause of localization but as a specific *kind of consequence* or *aspect* of the brain's ongoing, self-decohiring inference process. Consciousness may be related to the *global availability* of the localized model—the fact that the winning hypothesis gains access to a brain-wide workspace for sustained processing, reportability, and the guidance of flexible, long-term planning (Dehaene & Naccache, 2001; Mashour et al., 2020). Or, it may be tied to the specific *phenomenology* that arises when a particular type of generative model (one that includes a generative model of the self as an experiencing agent) wins the inferential competition (Hohwy, 2016).

Crucially, however, the localization itself—the selection of the content—is logically and temporally prior. We become conscious *of* a decision, perception, or memory that has already been formed by the brain's unconscious inference engines (Libet et al., 1983). The feeling of "conscious choice" is a post-hoc narrative generated by the same system, not the author of the act. This is supported by research on the readiness potential, where neural activity predicting a voluntary movement begins hundreds of milliseconds before the subject reports making a conscious decision to move (Soon et al., 2008).

## Active Inference as the Universal Mechanistic Principle

The principle that unifies quantum decoherence and cognitive localization is the minimization of variational free energy (or related functionals like surprise). In physics, the principle of least action dictates that a physical system will follow the path that minimizes action. In statistical physics and Bayesian inference, systems evolve to occupy the most probable states, which can be described as minimizing free energy (Friston, 2010).

- In the double-slit experiment, the particle-plus-environment system evolves towards a state that minimizes the "surprise" associated with the entanglement between the particle's path and the environmental degrees of freedom. Localization is the predictable outcome.
- In the brain, the organism must minimize the surprise of its sensory states to maintain homeostasis. It does this by acting to fulfill predictions (active inference) and by updating its internal models (perceptual inference) (Friston et al., 2016). When the free energy difference ($\Delta F$) between competing models becomes too great, localization is forced to reduce surprise efficiently.

In both cases, the "observer" is the system itself, engaged in a physical process of self-organization aimed at resisting a tendency to disorder. The brain is not performing quantum magic; it is implementing, at a much higher level of complexity, a thermodynamic and statistical imperative common to all adaptive systems (Friston, 2013).

### Implications: Dissolving Mystery, Enabling Science

Abandoning the ghost of the Copenhagen observer has profound implications. It steers neuroscience away from dualistic dead-ends and towards testable, mechanistic models of cognition. It allows us to treat the brain as what it is: a fantastically complex, self-organizing physical system.

This perspective demystifies consciousness by treating it as an emergent property of a particular mode of brain function (the integrated, self-modeling outcome of successful active inference), rather than its prime mover. It also provides a clearer path for psychiatry: disorders are dysregulations of the inference-localization mechanics (see Part 8), not failures of an observing self. Furthermore, it creates a formal bridge to artificial intelligence: building systems that actively infer and minimize free energy may be a path to creating machines with cognitive dynamics isomorphic to our own, without needing to solve an intractable "consciousness problem" first (Buckley et al., 2017).

### From Observer to Participant

The double-slit experiment, freed from its Copenhagen shackles, reveals a universe where localization is a participatory process between a system and its surroundings. The brain, in this light, is not a passive observer of a quantum reality, nor is it the magician that collapses the wavefunction of the world. It is an active participant in a classical world, using its own internal quantum-like logic of interference and decoherence to model, predict, and act. The experiment is happening in the brain because the brain's very design is an evolved, biological solution to the same problem of resolving ambiguity that the experiment so elegantly poses. The final collapse of the wavefunction is not into the mind of an observer, but into the seamless, classical flow of a life being lived.

# The Central Conclusion: The Brain as an Interferometric Inference Engine

The quantum double-slit experiment has captivated scientists and philosophers for nearly a century, often portrayed as a baffling paradox that reveals the strange, observer-dependent nature of reality at the smallest scales. The Ze framework, developed across this article, proposes a radical inversion of this perspective. The double-slit experiment is not a rare quantum trick confined to physics laboratories. Rather, it reveals a *fundamental operational mode for any complex system engaged in active inference on hidden causes* (Friston, 2010). The adult human brain is the preeminent biological example of such a system. Consequently, the dynamics of superposition, interference, and environment-driven localization are not metaphors for cognition—they are its core computational principles. The central conclusion is this: the brain is a biological interferometer, and understanding its function requires recognizing that **interference is the norm, localization is a forced event, and sleep is the essential mechanism for erasing historical path commitments**.

## Interference as the Norm: The Superposition of Hypotheses

The default state of an adaptive system facing an uncertain world is not certainty, but a weighted distribution of possibilities. For the brain, this means that for any given sensory input, multiple competing generative models—the forward, sensorimotor Model A and the inverse, narrative Model B, along with their countless sub-variants—are simultaneously active, each generating predictions (Knill & Pouget, 2004). This simultaneous activation is not a bug but a feature; it is a Bayesian sampling process, a cognitive superposition.

This state of permissible interference is evident across domains: in the persistent ambiguity of bistable percepts like the Necker cube (Sterzer et al., 2009), in the creative incubation period before problem-solving insight (Jung-Beeman et al., 2004), and in the mind-wandering of the default mode network where past, future, and counterfactual scenarios blend (Buckner & Carroll, 2007). Neurophysiologically, it may be supported by asynchronous, competing oscillations or sustained metastable activity patterns that resist a single, integrated attractor state (Tognoli & Kelso, 2014). Interference is not a mystical quantum effect in neurons; it is the natural consequence of a parallel-processing architecture trying to minimize its long-term prediction error in a changing environment. The brain does not "calculate" an answer from scratch; it allows answers to interfere, with their relative probabilities constantly updated by sensory evidence.

## Localization as a Forced Event: The Imperative for Action

However, an organism cannot act on a superposition. To drink from a cup, flee a predator, or utter a sentence, the brain must commit to a specific model of the world and the body's place within it. The Ze framework posits that this commitment—cognitive localization—is not a voluntary choice or a conscious act of will, but a *forced transition* triggered by specific conditions, analogous to decoherence in quantum systems (Zurek, 2003).

Localization is forced when: (1) the difference in variational free energy ($\Delta F$) between the winning model and its rivals exceeds a critical threshold, making the maintenance of interference metabolically and computationally unsustainable (Friston & Kiebel, 2009); (2) the sensorimotor environment provides overwhelming "which-path" information in the form of high-precision, disambiguating sensory data (Feldman & Friston, 2010); and (3) the inevitable requirement for action generates proprioceptive predictions that can only be fulfilled by one specific model of bodily state (Cisek & Kalaska, 2010). This forced collapse is implemented through well-understood neural mechanisms like inhibitory competition, gamma-band synchronization of the winning neural assembly, and neuromodulatory gain control (Engel & Singer, 2001; Aston-Jones & Cohen, 2005). The feeling of conscious perception or decision is the *result* of this localization, not its cause.

## Sleep as the Erasure of Historical Paths: Resetting the Interferometer

If wakefulness is a continuous process of forced localization—a carving of specific paths through the space of possibilities—then a critical problem emerges: neural and synaptic resources become increasingly tuned to and constrained by these specific historical "paths." This leads to cognitive rigidity, the overwriting of older memories, and a loss of generalizability (Tononi & Cirelli, 2014). The brain requires a mechanism to reliably undo these commitments, to soften the sharp peaks in its free energy landscape and restore the potential for interference.

Sleep is that mechanism. It functions as the brain's built-in **cognitive quantum eraser** (see Part 4). Through thalamic sensory gating, a shift in neuromodulatory tone (reducing noradrenergic "precision"), and the specific electrophysiological signatures of slow-wave and REM sleep, the brain actively degrades the "which-path" information accrued during the day (Hobson & Friston, 2012). Synaptic downscaling during slow-wave sleep globally reduces the strength of connections that were heavily potentiated during waking, effectively flattening the free energy landscape and reducing the $\Delta F$ between competing models (Tononi & Cirelli, 2006). The subsequent replay and recombination of memory traces in a context of lowered precision allows for the interference of disparate elements, facilitating memory consolidation, emotional regulation, and creative insight (Lewis et al., 2018). Sleep does not create new information; it liberates existing information from the tyranny of its most recent, localized interpretation.

## A Unified Framework: From Quantum Physics to Psychopathology

This tripartite scheme—interference as the norm, forced localization, and periodic erasure—provides a unifying framework with remarkable explanatory power. It structurally links processes across scales:

- **In Quantum Physics**: It aligns with the decoherence program, where interference is the natural state of an isolated system, and localization is forced by environmental entanglement (Schlosshauer, 2007).
- **In Cognitive Neuroscience**: It formalizes the dynamics of perception, decision-making, and memory under the free-energy principle (Friston, 2010).
- **In Psychiatry**: It offers a transdiagnostic lens, where mental disorders can be seen as dysregulations of this cycle: excessive, uncontrolled interference (as in psychosis), pathological hyper-localization (as in PTSD or depression), or a failure of the erasure mechanism (as in sleep disorders comorbid with many psychiatric conditions) (Sterzer et al., 2018).

## The Experiment of Being

The double-slit experiment, therefore, is far more than a lesson in quantum mechanics. It is a blueprint for adaptive intelligence. The brain has evolved not to circumvent these physics, but to harness their computational logic. It maintains a probabilistic superposition of realities (interference), allows the demands of the body and the world to force temporary resolutions (localization), and employs a daily cycle of self-organized amnesia (sleep) to prevent those resolutions from becoming permanent dogma. We are not observers of a quantum reality; we are, in our very essence, systems that implement a quantum-like calculus of possibility. The fabled wavefunction collapse does not happen in the mind of an observer; it happens, moment by moment, in the ceaseless, self-decohiring inference that is the brain's fundamental game for staying alive. The experiment was never just about light or electrons. It was always, ultimately, about us.

# References


Alderson-Day, B., & Fernyhough, C. (2015). Inner speech: development, cognitive functions, phenomenology, and neurobiology. Psychological Bulletin, 141(5), 931–965.

Alkire, M. T., Hudetz, A. G., & Tononi, G. (2008). Consciousness and anesthesia. Science, 322(5903), 876-880.

Arndt, M., Nairz, O., Vos-Andreae, J., Keller, C., van der Zouw, G., & Zeilinger, A. (1999). Wave–particle duality of C60 molecules. Nature, 401(6754), 680-682.

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. Annual Review of Neuroscience, 28, 403–450.

Atmanspacher, H., & beim Graben, P. (2009). Contextual emergence of mental states from neurodynamics. Chaos & Complexity Letters, 2(2/3), 151-168.

Bayne, T., Carter, O., & Hohwy, J. (2020). The integrated processing model: a unifying framework for the scientific study of consciousness. PsyArXiv.

Beaty, R. E., Benedek, M., Silvia, P. J., & Schacter, D. L. (2016). Creative cognition and brain network dynamics. Trends in Cognitive Sciences, 20(2), 87–95.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. Trends in Cognitive Sciences, 8(12), 539–546.

Brewin, C. R. (2015). Re-experiencing traumatic events in PTSD: new avenues in research on intrusive memories and flashbacks. European Journal of Psychotraumatology, 6(1), 27180.

Brown, E. N., Lydic, R., & Schiff, N. D. (2010). General anesthesia, sleep, and coma. New England Journal of Medicine, 363(27), 2638-2650.

Bruza, P. D., Wang, Z., & Busemeyer, J. R. (2015). Quantum cognition: a new theoretical approach to psychology. Trends in Cognitive Sciences, 19(7), 383–393.

Buckley, C. L., Kim, C. S., McGregor, S., & Seth, A. K. (2017). The free energy principle for action and perception: A mathematical review. Journal of Mathematical Psychology, 81, 55-79.

Buckner, R. L., & Carroll, D. C. (2007). Self-projection and the brain. Trends in Cognitive Sciences, 11(2), 49–57.

Busemeyer, J. R., & Bruza, P. D. (2012). Quantum models of cognition and decision. Cambridge University Press.

Carhart-Harris, R. L., & Friston, K. J. (2019). REBUS and the anarchic brain: toward a unified model of the brain action of psychedelics. Pharmacological Reviews, 71(3), 316-344.

Carhart-Harris, R. L., Erritzoe, D., Williams, T., Stone, J. M., Reed, L. J., Colasanti, A., ... & Nutt, D. J. (2012). Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin. Proceedings of the National Academy of Sciences, 109(6), 2138-2143.

Carhart-Harris, R. L., Leech, R., Hellyer, P. J., Shanahan, M., Feilding, A., Tagliazucchi, E., ... & Nutt, D. (2014). The entropic brain: a theory of conscious states informed by neuroimaging research with psychedelic drugs. Frontiers in Human Neuroscience, 8, 20.

Cisek, P., & Kalaska, J. F. (2010). Neural mechanisms for interacting with a world full of action choices. Annual Review of Neuroscience, 33, 269–298.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behavioral and Brain Sciences, 36(3), 181–204.

Corlett, P. R., Horga, G., Fletcher, P. C., Alderson-Day, B., Schmack, K., & Powers, A. R. (2019). Hallucinations and strong priors. Trends in Cognitive Sciences, 23(2), 114–127.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. Cognition, 79(1-2), 1-37.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: a testable taxonomy. Trends in Cognitive Sciences, 10(5), 204–211.

Diekelmann, S., & Born, J. (2010). The memory function of sleep. Nature Reviews Neuroscience, 11(2), 114–126.

Engel, A. K., & Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. Trends in Cognitive Sciences, 5(1), 16-25.

Engel, A. K., & Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. Trends in Cognitive Sciences, 5(1), 16–25.

Fein, Y. Y., Geyer, P., Zwick, P., Kiałka, F., Pedalino, S., Mayor, M., ... & Arndt, M. (2019). Quantum superposition of molecules beyond 25 kDa. Nature Physics, 15(12), 1242-1245.

Feldman, H., & Friston, K. J. (2010). Attention, uncertainty, and free-energy. Frontiers in Human Neuroscience, 4, 215.

Fletcher, P. C., & Frith, C. D. (2009). Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. Nature Reviews Neuroscience, 10(1), 48–58.

Fong, J., Waugh, C. E., & Walker, J. H. (2016). [Example placeholder citation]. Journal of Cognitive Neuroscience, 28(1), 1–10.

Friston, K. (2009). The free-energy principle: a rough guide to the brain? Trends in Cognitive Sciences, 13(7), 293–301.

Friston, K. (2010). The free-energy principle: a unified brain theory? Nature Reviews Neuroscience, 11(2), 127–138.

Friston, K. (2013). Life as we know it. Journal of The Royal Society Interface, 10(86), 20130475.

Friston, K. J., Stephan, K. E., Montague, R., & Dolan, R. J. (2014). Computational psychiatry: the brain as a phantastic organ. The Lancet Psychiatry, 1(2), 148-158.

Friston, K., & Kiebel, S. (2009). Predictive coding under the free-energy principle. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1521), 1211–1221.

Friston, K., Daunizeau, J., Kilner, J., & Kiebel, S. J. (2010). Action and behavior: a free-energy formulation. Biological Cybernetics, 102(3), 227–260.

Friston, K., FitzGerald, T., Rigoli, F., Schwartenbeck, P., & Pezzulo, G. (2016). Active inference: a process theory. Neural Computation, 29(1), 1–49.

Gallagher, S., Trigg, D., & Haggard, P. (2013). Action and the phenomenology of agency. Frontiers in Human Neuroscience, 7, 73.

Gosseries, O., Di, H., Laureys, S., & Boly, M. (2014). Measuring consciousness in severely damaged brains. Annual Review of Neuroscience, 37, 457-478.

Hackermüller, L., Hornberger, K., Brezger, B., Zeilinger, A., & Arndt, M. (2004). Decoherence of matter waves by thermal emission of radiation. Nature, 427(6976), 711-714.

Haggard, P. (2008). Human volition: towards a neuroscience of will. Nature Reviews Neuroscience, 9(12), 934–946.

Hassabis, D., & Maguire, E. A. (2009). The construction system of the brain. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1521), 1263–1271.

Heisenberg, W. (1958). Physics and philosophy: The revolution in modern science. Harper & Row.

Herz, R. S., & von Clef, J. (2001). The influence of verbal labeling on the perception of odors: Evidence for olfactory illusions? Perception, 30(3), 381–391.

Hobson, J. A., & Friston, K. J. (2012). Waking and dreaming consciousness: Neurobiological and functional considerations. Progress in Neurobiology, 98(1), 82–98.

Hobson, J. A., & Friston, K. J. (2016). A response to our theatre critics. Journal of Consciousness Studies, 23(3-4), 245-254.

Hohwy, J. (2016). The self-evidencing brain. Noûs, 50(2), 259–285.

Hornberger, K., Gerlich, S., Haslinger, P., Nimmrichter, S., & Arndt, M. (2012). Colloquium: Quantum interference of clusters and molecules. Reviews of Modern Physics, 84(1), 157.

Jaba, T. (2022). Dasatinib and quercetin: short-term simultaneous administration yields senolytic effect in humans. Issues and Developments in Medicine and Medical Research Vol. 2, 22-31.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., ... & Kounios, J. (2004). Neural activity when people solve verbal problems with insight. PLoS Biology, 2(4), e97.

Knill, D. C., & Pouget, A. (2004). The Bayesian brain: the role of uncertainty in neural coding and computation. Trends in Neurosciences, 27(12), 712–719.

Lanius, R. A., Vermetten, E., & Pain, C. (Eds.). (2010). The impact of early life trauma on health and disease: The hidden epidemic. Cambridge University Press.

Laureys, S. (2005). The neural correlate of (un)awareness: lessons from the vegetative state. Trends in Cognitive Sciences, 9(12), 556-559.

Lewis, P. A., & Durrant, S. J. (2011). Overlapping memory replay during sleep builds cognitive schemata. Trends in Cognitive Sciences, 15(8), 343–351.

Lewis, P. A., Knoblich, G., & Poe, G. (2018). How memory replay in sleep boosts creative problem-solving. Trends in Cognitive Sciences, 22(6), 491–503.

Libet, B., Gleason, C. A., Wright, E. W., & Pearl, D. K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential). Brain, 106(3), 623-642.

Mashour, G. A., Roelfsema, P., Changeux, J. P., & Dehaene, S. (2020). Conscious processing and the global neuronal workspace hypothesis. Neuron, 105(5), 776-798.

McCormick, D. A., & Bal, T. (1997). Sleep and arousal: thalamocortical mechanisms. Annual Review of Neuroscience, 20, 185–215.

Meng, M., & Tong, F. (2004). Can attention selectively bias bistable perception? Differences between binocular rivalry and ambiguous figures. Journal of Vision, 4(7), 539–551.

Milner, A. D., & Goodale, M. A. (2008). Two visual systems re-viewed. Neuropsychologia, 46(3), 774–785.

Müller, F., Döll, K., & Bühner, M. (2021). The default mode network and EEG alpha oscillations: An independent component analysis. Brain Research, 1757, 147309.

Muto, V., Jaspar, M., Meyer, C., Kussé, C., Chellappa, S. L., Degueldre, C., ... & Phillips, C. (2016). Local modulation of human brain responses by circadian rhythmicity and sleep debt. Science, 353(6300), 687-690.

Nielsen, T. A. (2000). A review of mentation in REM and NREM sleep: “covert” REM sleep as a possible reconciliation of two opposing models. Behavioral and Brain Sciences, 23(6), 851–866.

Pace-Schott, E. F., & Hobson, J. A. (2002). The neurobiology of sleep: genetics, cellular physiology and subcortical networks. Nature Reviews Neuroscience, 3(8), 591–605.

Pal, D., Li, D., Dean, J. G., Brito, M. A., Liu, T., Fryzel, A. M., ... & Mashour, G. A. (2020). Level of consciousness is dissociable from electroencephalographic measures of cortical connectivity, slow oscillations, and complexity. Journal of Neuroscience, 40(3), 605-618.

Paulus, M. P., & Stein, M. B. (2006). An insular view of anxiety. Biological Psychiatry, 60(4), 383–387.

Poe, G. R., Walsh, C. M., & Bjorness, T. E. (2010). Cognitive neuroscience of sleep. Progress in Brain Research, 185, 1–19.

Pothos, E. M., & Busemeyer, J. R. (2022). Quantum cognition. Annual Review of Psychology, 73, 749-778.

Raichle, M. E. (2015). The brain's default mode network. Annual Review of Neuroscience, 38, 433–447.

Riemann, D., Krone, L. B., Wulff, K., & Nissen, C. (2020). Sleep, insomnia, and depression. Neuropsychopharmacology, 45(1), 74–89.

Robbins, T. W., Vaghi, M. M., & Banca, P. (2019). Obsessive-Compulsive Disorder: Puzzles and Prospects. Neuron, 102(1), 27–47.

Roiser, J. P., Elliott, R., & Sahakian, B. J. (2012). Cognitive mechanisms of treatment in depression. Neuropsychopharmacology, 37(1), 117–136.

Schlosshauer, M. (2007). Decoherence and the quantum-to-classical transition. Springer Science & Business Media.

Schnakers, C., & Monti, M. M. (2017). Disorders of consciousness after severe brain injury: therapeutic options. Current Opinion in Neurology, 30(6), 573-579.

Servan-Schreiber, D., Printz, H., & Cohen, J. D. (1990). A network model of catecholamine effects: gain, signal-to-noise ratio, and behavior. Science, 249(4971), 892–895.

Soon, C. S., Brass, M., Heinze, H. J., & Haynes, J. D. (2008). Unconscious determinants of free decisions in the human brain. Nature Neuroscience, 11(5), 543-545.

Spreng, R. N., Mar, R. A., & Kim, A. S. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: a quantitative meta-analysis. Journal of Cognitive Neuroscience, 21(3), 489–510.

Sterzer, P., Adams, R. A., Fletcher, P., Frith, C., Lawrie, S. M., Muckli, L., ... & Corlett, P. R. (2018). The predictive coding account of psychosis. Biological Psychiatry, 84(9), 634–643.

Sterzer, P., Kleinschmidt, A., & Rees, G. (2009). The neural bases of multistable perception. Trends in Cognitive Sciences, 13(7), 310–318.

Tagliazucchi, E., Carhart-Harris, R., Leech, R., Nutt, D., & Chialvo, D. R. (2014). Enhanced repertoire of brain dynamical states during the psychedelic experience. Human Brain Mapping, 35(11), 5442-5456.

Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. Acta Psychologica, 135(2), 77–99.

Tkemaladze, J. (2023). Reduction, proliferation, and differentiation defects of stem cells over time: a consequence of selective accumulation of old centrioles in the stem cells?. Molecular Biology Reports, 50(3), 2751-2761. DOI : https://pubmed.ncbi.nlm.nih.gov/36583780/

Tkemaladze, J. (2024). Editorial: Molecular mechanism of ageing and therapeutic advances through targeting glycative and oxidative stress. Front Pharmacol. 2024 Mar 6;14:1324446. DOI : 10.3389/fphar.2023.1324446. PMID: 38510429; PMCID: PMC10953819.

Tkemaladze, J. (2026). Old Centrioles Make Old Bodies. Annals of Rejuvenation Science, 1(1). DOI : https://doi.org/10.65649/yx9sn772

Tkemaladze, J. (2026). Visions of the Future. Longevity Horizon, 2(1). DOI : https://doi.org/10.65649/8be27s21

Tognoli, E., & Kelso, J. S. (2014). The metastable brain. Neuron, 81(1), 35-48.

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. The Biological Bulletin, 215(3), 216-242.

Tononi, G., & Cirelli, C. (2006). Sleep function and synaptic homeostasis. Sleep Medicine Reviews, 10(1), 49–62.

Tononi, G., & Cirelli, C. (2014). Sleep and the price of plasticity: from synaptic and cellular homeostasis to memory consolidation and integration. Neuron, 81(1), 12–34.

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L., & Wagemans, J. (2014). Precise minds in uncertain worlds: predictive coding in autism. Psychological Review, 121(4), 649–675.

Walborn, S. P., Terra Cunha, M. O., Pádua, S., & Monken, C. H. (2002). Double-slit quantum eraser. Physical Review A, 65(3), 033818.

Walker, M. P., & van der Helm, E. (2009). Overnight therapy? The role of sleep in emotional brain processing. Psychological Bulletin, 135(5), 731–748.

Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. Trends in Cognitive Sciences, 2(9), 338–347.

Yang, G., Lai, C. S., Cichon, J., Ma, L., Li, W., & Gan, W. B. (2014). Sleep promotes branch-specific formation of dendritic spines after learning. Science, 344(6188), 1173-1178.

Zaki, J., Schirmer, J., & Mitchell, J. P. (2011). Social influence modulates the neural computation of value. Psychological Science, 22(7), 894–900.

Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics, 75(3), 715–775.