

Core and Matrix Thalamic Nuclei: Parallel Circuits Involved in Content of Experience and General Wakefulness

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ABSTRACT

During development, the brain creates multilevel feedback loops critical for the generation and maintenance of consciousness. The thalamus has a central role in these circuits. Thalamic *core* nuclei are part of sensory circuits that give rise to contents of experience; diffuse thalamic *matrix* nuclei are part of arousal circuits that modulate levels of wakefulness. While *core* and *matrix* circuits could be considered part of a single brain system underlying conscious experience, they can also be seen as discrete, parallel circuits responsible for content and consciousness, respectively. Reverberations in thalamocortical *core* circuits, driven by tasks and conditions, encode content. Reverberations in matrix circuits, driven by circadian rhythms and the “value” of experience, encode fluctuations in arousal levels. This paper considers contributions of quantum events at cellular levels to activation in thalamic matrix circuits. Considering both quantum and classical brain processing gives insight into the relation of brain functioning and consciousness.

Key Words: Quantum effects; thalamic loops; consciousness; matrix cells

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Introduction

We live in a 3-dimensional world measured in inches and seconds. Objects follow predictable laws. If you drop a pen, it will land on the floor. If you pour water into a glass, it will fill the glass and stay in the glass.

In contrast, the atoms of our brain live in a world that is 10 million times smaller than ordinary experience, and objects in that world follow different rules. Electrons are not particles; rather, they are both a particle and a wave, depending on how they are measured. Or it may be more accurate to say that they are neither a particle nor a wave. They are the *quantum superimposition* of both realities until we make a measurement and collapse the wave function to a wave or particle (Eisberg and Resnick, 1985).

The brain can be understood as a classical structure that encodes the world in action potentials within neural circuits comprising millions of neurons. The brain can also be understood in terms of quantum events at the neuronal level, *i.e.*, quantum superimposition, quantum uncertainty, and quantum tunneling. These quantum events co-exist with classical brain processes. By looking at both together—superimposition of both quantum and classical events—we may gain insight into the relation of brain functioning and consciousness.

Classical Brain Dynamics and Consciousness Experience The brain builds feedback circuits

The brain undergoes major structural and functional reorganization in the first two decades of life. These transformations are driven by natural maturation guided by biological information in the DNA (Sowell and Thompson, 2004; Sowell and Trauner, 2002) interacting with ongoing experience (Elbert and Pantev, 1995; Imfeld and Oechslein, 2009). Bursts in brain growth, measured by larger

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head circumferences, higher peak resting EEG (Epstein, 1986), and higher cerebral blood flow (Epstein, 1999) are correlated with transitions in Piagetian stages of reasoning (Epstein, 2001) and in ego development (Snarey, 1986). These developmental processes create circuits functionally coupled by reciprocal connections linking spatially dispersed regions in the cortex (Varela and Lachaux, 2001). The neural circuits that develop are formed into feedback circuits—parallel connections between brain areas.

Edelman has described these feedback circuits as “reentrant circuits” in his Neural Darwinism model (Edelman and Gally, 2011; Edelman and Tononi, 2000). Reentrant circuits comprise massively parallel connections that support ongoing reciprocal signaling between distinct brain areas. They maintain synchronous time-locked patterns of activity that integrate output from different brain areas and last for 100s of milliseconds or longer—long enough to lead to sensory experience or to generate an intended template for action. By introducing previous brain states into current processes, reentrant circuits allow the brain to “speak to itself,” a necessary basis for memory and thought (Edelman and Gally, 2011).

The dynamic core—the reticular activating system, thalamus and cortex

The reticular activating system, thalamus and cortex constitute a “dynamic core;” lesions to these structures remove the possibility of conscious experience (Edelman and Tononi, 2000). The reticular activating system is responsible for arousal and for governing the waking/sleeping transition (Magoun, 1952). The thalamus plays a central role in the dynamic core. It is the “switchboard” of action potentials from the sensory and motor systems to the cortex. Afferents from the reticular activating system project to the thalamus and then up to the cortex (Steriade, 1996). These circuits shift attention levels and lead to desynchronized EEG and gamma activity (Steriade, 1995).

Different targets of thalamic core and matrix nuclei

The thalamus contains two major types of cells—*core* and *matrix* neurons—that have been delineated with staining techniques (Jones, 2001). Thalamocortical *core* nuclei

project to the prefrontal and parietal cortices, known to be involved in representing sensory input and externally-directed attention; thalamocortical *matrix* nuclei project to brain regions involved in higher-order cognitive processing, self-awareness and introspective thinking—the dorsal prefrontal and anterior cingulate cortices (Zhou, Liu, 2011).

The thalamic *core* cells are spatially distinct and project sensory-specific information to cortical Layer IV. A period of sustained hypopolarization in thalamic core nuclei results in a well-defined re-entrant activation pattern in sensory- motor circuits that is associated with the content of conscious experience (Seth and Baars, 2005). The thalamic *matrix* cells activate a more diffuse cortical area (Liu and Jones, 1999). The matrix cells are dispersed throughout the thalamus and fire up to cortical Layer I. Neurons in all cortical layers, except for Layer IV, have their distal processes in Layer I. Thus, controlling arousal levels of cortical Layer I would modulate generalized wakefulness or alertness of the other cortical layers. Reverberations in matrix circuits might serve as a coincidence detection circuit—promoting synchronous activity in adjacent cortical columns—as a spotlight that illumines the most important ongoing experience (Baars, 2002).

Content of experience versus inner subjectivity

The *core* and *matrix* circuits work together to create sensory-motor awareness leading to purposeful behavior (Llinas and Steriade, 2006; Steriade, 2006). Thus, *core* and *matrix* circuits could be considered part of a single brain system underlying conscious experience. Input that is consciously experienced first activates sensory cortices (via thalamic *core* circuits) and then spreads to prefrontal and medial-temporal cortices (via thalamic *matrix* circuits).

However, activity in these two circuits can be dissociated. Closely matched input that is not reported activates only local sensory regions (Baars, 2002). Libet reported that a cortical sensory area would need to be stimulated for 500 msec before the patient reported sensory experience (Libet, 1982; Libet and Pearl, 1991). It is interesting in this study that the continuity of the patient’s wakefulness did not change, only the content in consciousness. Another example, during



sleep, thalamic *core* circuits can activate Layer IV of the sensory cortex, as evidenced by *K*-complexes in the sleep EEG, but thalamic *matrix* circuits are hyperpolarized. Consequently, the cortex is not sufficiently aroused to process the volley of incoming sensory information and there is no conscious awareness of environmental stimuli (Steriade and McCormick, 1993).

The thalamic *core* and *matrix* neurons may be discrete, parallel circuits that are responsible for content and consciousness, respectively. Reverberations in thalamocortical *core* circuits are driven by tasks and conditions (Jones, 2001, Llinas and Steriade, 2006). They hold online temporally and spatially consistent features of stimuli such as size, shape, and color. Lifelike pictures of the world do not move through our sensory system. Rather, objects are broken down into patterns of action potentials that create a “hilly” surface defined by neural firing rates. If these reverberations continue for 100s of msec, they generate the content of experience. For instance, Freeman has reported different patterns of firing in the rabbit’s olfactory bulb in response to different odors (Freeman, 2006; Kozma and Freeman, 2008). He found that the pattern of firing rates of the olfactory bulb was always the same for the same odor, and different for different odors. This is the job of the *core* thalamocortical circuits: to encode patterns of sensory information in reverberating patterns of neural firing long enough so we can experience the object.

If reverberations in thalamocortical *core* circuits encode content; what do reverberations in thalamocortical *matrix* circuits encode? Thalamocortical *matrix* circuits also generate a pattern of firing rates to the cortex, but their firing is driven by slow changes in 24-hour circadian rhythms of wakefulness driven by the hypothalamus, and by saliency or value of different experiences such as level of pleasure, pain, or emotional content (Edelman and Gally, 2011). The “content” of matrix circuits may be wakefulness itself. Reverberations in matrix circuits do not encode perceptual features; rather they encode fluctuations in waking or arousal levels. These continuously changing states of thalamocortical matrix circuits could define levels of “wakefulness.” Past states based on past “value” would feed into current states creating a dynamically changing

continuum of wakefulness. This state would permeate all moment-by-moment experiences and may add the sense of “my” to experience—something relatively non-changing in comparison to rapidly changing sensory input. The ongoing states in thalamocortical matrix circuits could be related to qualia—how an experience feels to us (Nagel, 1974).

For instance, if you’re sitting in a lecture, your *core* circuits are bringing in the Power Point slides and the teacher’s logic; variations in your *matrix* circuits would determine whether you feel bored, neutral, or fascinated. Together these two reverberating circuits define our stream of consciousness—changing content within slowing shifting levels of wakefulness from morning to night.

Quantum Events and Thalamocortical Matrix Circuits

Up to this point, this paper has proceeded on steps of logic and inference rooted in neuroscience. This next section is more speculative. Quantum events have been described at the molecular level of the brain, including quantum superimposition of tubulin proteins in the microtubules of the cell, quantum superimposition of neurotransmitter vesicles within the synapse, quantum uncertainty of calcium dynamics in the synapse, and quantum tunneling. Quantum brain effects may not be isolated phenomena with one process more significant than another. Rather, they may together contribute towards activation at molecular levels (10^{-8} meters) that could bias brain states at the macroscopic level.

Quantum Superimposition of Tubulin in Microtubules

Hameroff and Penrose have elegantly and systematically detailed how quantum effects occurring within the microtubules of the cell might contribute to conscious experience (Hameroff and Penrose, 1996). Microtubules form the cytoskeleton of brain cells and carry out a range of functions, including providing structural support, transporting organelles throughout the cytoplasm, and aiding in cell division (Dayhoff and Hameroff, 1994; Hameroff and Watt, 1982). Tubulin proteins comprise the crystal-like lattice structure of microtubules. The conformational states of tubulin proteins are sensitive to internal



quantum events—London forces in hydrophobic pockets—and so exist in quantum coherent superimposition (Fröhlich, 1975). According to Penrose, quantum superimposition is displacement of mass from itself, which is equivalent to space-time geometry in opposite directions or unstable “bubbles.” The coupling between mass and deformations of space-time might cause an objective collapse of the wave function to classical states—objective reduction (Penrose, 1996). Objective reduction is posited to be tuned or “orchestrated” by microtubule associated proteins—leading to “orchestrated objective reduction” (Hameroff and Penrose, 1996). Quantum collapse is irreversible and so creates a feed forward cascade of events.

Quantum probability amplitudes and quantum uncertainty in the synapse

Action potentials move across the synapse with a probability of 0.2-0.4; it is a probabilistic phenomenon and so might be inherently quantum mechanical (Beck and Eccles, 1992; Beck, 2008). Beck and Eccles reason that neurotransmitter vesicles sit in a meta-stable grid in the presynaptic membrane. However, only one vesicle deposits its transmitter molecules into the synaptic cleft after each action potential reaches the axonal terminal. Before a vesicle deposits its contents into the synapse, the authors suggest that there is a quantum superimposition of all vesicles firing and not firing (Beck and Eccles, 1992). Selection of a specific vesicle may reflect shifting of quantum probability amplitudes.

Stapp proposes a different quantum effect in the synapse, namely in the dynamics of exocytosis itself (Stapp, 2007). When the action potential ends at the axon terminal, calcium ion channels—small slits one nanometer thick—open up in the pre-synaptic membrane. Calcium ions move through these slits into the interior of the cell. Due to the extremely narrow channels—about as wide as the calcium ion itself—lateral dispersion is restricted. Thus, the quantum probability cloud may not have high enough concentration to move synaptic vesicles to the membrane. Stapp suggests that the quantum uncertainty at individual calcium ion channels represents a quantum mixture of many classical states, each associated with a specific classical experience (Stapp, 2007).

Quantum tunneling in gap junctions

These quantum processes may well exist. However, they occur at time and distance scales that are far removed from human experience. Quantum events in proteins and across synapses need to be combined into “human” time frames to be able to affect conscious experiences. These microscopic quantum states could spread via quantum tunneling through gap junctions to affect macroscopic brain states.

Gap junctions are 3.5 nanometers wide breaks in the membrane that form primitive electronic windows between dendrites and dendrites and between dendrites and glia (Froes and de Carvalho, 1998). Cells interconnected by gap junctions form networks which fire synchronously, “behaving like one giant neuron” (Kandel, 1991). The concentration of gap junctions is highest in the dynamic core, which as we described earlier contains brain structures critical for conscious experience (Micevych and Abelson, 1991). The quantum states produced at molecular levels may spread through gap junctions in thalamocortical matrix circuits influencing brain-wide classical states. In this way, quantum events may contribute to classical phenomena.

Possible Relation of Quantum Events and Conscious Experiences

Reverberations within thalamocortical *matrix* circuits, previously tied to subjective awareness, may reflect contributions from both quantum events and from hypothalamic feedback mechanisms. Quantum events summed through quantum tunneling might maintain a baseline level of wakefulness, while circadian rhythms driven by hypothalamic feedback would be responsible for temporary changes in attention and arousal. The magnitude of quantum events—estimated to be 1×10^{22} operations/second/ neuron in each of the 10^{10} neurons in the brain (Hameroff and Penrose, 1996; Penrose, 1996)—suggests that they may not add specific bits of information to experience; specific bits of information would require discrete and changing patterns of activation. Rather, these quantum events may create a lively physiological state that, when perturbed by sensory stimulation, would generate a specific pattern associated with sensory processing (Faure and Korn, 2001; Korn and Faure, 2003). This lively



physiological state might function as a non-linear dynamic system that would not be random, but would respond to sensory–cognitive stimulation by generating the orderly, sequential generation of event-related components phase-locked to the stimulus (Başar and Karakas, 2006) and associated with specific content (Elbert and Ray, 1994).

Individual personality and pure consciousness

In light of this discussion, one individual personality might include reverberations in both *core* and *matrix* thalamic circuits. The content of experience, reflecting reverberation in *core* circuits, could be intertwined with awareness reflecting reverberation in *matrix* circuits. One might describe themselves in terms of external qualities—“I am six feet tall, weigh 175 lb, have a PhD in neuroscience, attend a specific church, think critically and am compassionate and respectful towards other traditions”.

Most models of brain and consciousness do not separate the contributions from *core* and *matrix* circuits. Edelman suggests that “primary consciousness” results from reentrant interactions between posterior areas of the brain that are involved with perceptual categorization, which would involve thalamic *core* cells, and anterior areas of the brain involved with value-based memory, which would involve thalamic *matrix* cells. Edelman calls this the concrete or immediate presence or the “remembered present” that adaptively

links immediate or imagined contingencies with value driven behavior (Edelman, 2003). This is similar to Damasio’s “core self” (Damasio and Dolan, 1999). Both of these models combine the output of the *core* and *matrix* circuits in discussing conscious experience. This is understandable since both content and consciousness are required to report an experience, and in most brain and consciousness models, consciousness is defined as perceptual awareness or the ability to report experiences (Baars, 2002).

In contrast, meditation experiences discuss another dimension of consciousness, called “pure consciousness,” in which self-awareness is described not in terms of qualities but is described by the absence of qualities—hence the term “pure” (Maharishi, 1969; Travis and Pearson, 2000). This experience of pure consciousness could reflect dampening of reverberations in the thalamic *core* nuclei while maintaining reverberations in *matrix* nuclei. In addition, if the physiology is in a quiet state and one is not disturbed, the contributions of physiological feedback mechanisms may be minimized leaving the contribution of quantum events as the primary determinant of *matrix* circuit dynamics. Thus, the experience of pure consciousness, which is described as a state outside of time, space and body sense (Travis and Pearson, 2000), could be the experience of the innumerable quantum events at the microscopic level of the brain summed by quantum tunneling to become a direct experience.



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