

The Brain Is Both Neurocomputer and Quantum Computer

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Abstract

In their article, *Is the Brain a Quantum Computer?* Litt, Eliasmith, Kroon, Weinstein, and Thagard (2006) criticize the Penrose–Hameroff “Orch OR” quantum computational model of consciousness, arguing instead for neurocomputation as an explanation for mental phenomena. Here I clarify and defend Orch OR, show how Orch OR and neurocomputation are compatible, and question whether neurocomputation alone can physiologically account for coherent gamma synchrony EEG, a candidate for the neural correlate of consciousness. Orch OR is based on quantum computation in microtubules within dendrites in cortex and other regions linked by dendritic–dendritic gap junctions (“dendritic webs”) acting as laterally connected input layers of the brain’s neurocomputational architecture. Within dendritic webs, consciousness is proposed to occur as gamma EEG-synchronized sequences of discrete quantum computational events acting in integration phases of neurocomputational “integrate-and-fire” cycles. Orch OR is a viable approach toward understanding how the brain produces consciousness.

Keywords: Consciousness; Neurocomputation; Quantum computation; Microtubules; Orchestrated objective reduction (Orch OR); Gamma synchrony; EEG; Dendritic webs; Gap junctions; Anesthesia; Integrate and fire

1. Neurocomputation and quantum computation are compatible—“Dendritic webs”

In their article, *Is the brain a quantum computer?*, Litt, Eliasmith, Kroon, Weinstein, and Thagard (2006) argue that “neurocomputational rather than quantum mechanisms provide the most credible explanations of mental phenomena” (p. 594), and criticize (among other quantum consciousness theories) the Orch OR (“orchestrated objective reduction”) model put

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forth by Sir Roger Penrose and me (Hameroff & Penrose, 1996a, 1996b; Hameroff, 1998c; Hameroff, 2006a; Penrose & Hameroff, 1995).

By *neurocomputational* I assume Litt et al. (2006) imply computation mediated by axonal action potentials (*firings* or *spikes*) and axonal-dendritic (or axonal-somatic) chemical synaptic connections of variable strength between neurons. In this neural network paradigm, individual dendrites of each neuron receive and integrate multiple input-generated post-synaptic potentials, and when threshold is met, “fire”—that is, trigger axonal action potential spikes as outputs (“integrate and fire”).

In the Orch OR model, quantum computations are proposed to occur in microtubules in cytoplasm within gap junction-linked dendrites (dendritic webs; see Fig. 1) of these same brain neurons in cortex and other regions (i.e. embedded in integration phases of integrate-and-fire cycles). The proposed quantum computations/integrations are discrete events of roughly 25 msec duration (coupled to gamma synchrony EEG) with each quantum computation culminating in a conscious moment (e.g., at 40 Hz). In neural network parlance, the site of consciousness is proposed to occur in laterally-connected inputs of a hidden layer, able to selectively trigger axonal firings as outputs in specific neurons and thus govern behavior. Orch OR and neurocomputation are compatible, and consciousness may occur primarily in dendrites, as proposed previously by Karl Pribram (1991), Sir John Eccles (1992), and others.

2. Specific issues in *Is the Brain a Quantum Computer?*

Here I respond to specific issues raised by Litt et al. (2006) in their article.

2.1. *Nothing special about microtubules*

Litt et al. state “Found throughout the plant and animal kingdoms, their distribution in neurons is wholly unexceptional” (p. 597). This is false. (a) Brain neuronal microtubules are composed of 17 different isozymes of subunit proteins (“tubulins”), far greater genetic diversity (and information capacity) than microtubules in other cells (Lee, Field, George, & Head, 1986); (b) microtubules are densely arrayed and overly abundant in neurons compared to all other cells because of the large and highly asymmetrical neuronal shape; (c) only neuronal dendrites have mixed polarity, short microtubules interconnected in anti-parallel network arrays (e.g., Woolf, 1998; Woolf & Hameroff, 2001) simulations of which are suitable for learning (Rasmussen, Karampurwala, Vaidyanath, Jensen, & Hameroff, 1990); (d) only in the brain are many such arrays interconnected in gap junction-linked dendritic webs.

Orch OR attributes consciousness to a sequence of discrete conscious moments, each a quantum computation terminated by an objective threshold for quantum state reduction proposed by Penrose (objective reduction—OR). The quantum computations in dendritic microtubules are proposed to be “orchestrated” by axonal firings, synaptic inputs, memory, etc. (hence, Orch OR).

According to Orch OR, dendritic cytoplasmic microtubules are isolated from their classical/non-quantum environment (e.g., by actin gelation) in quantum state phases of

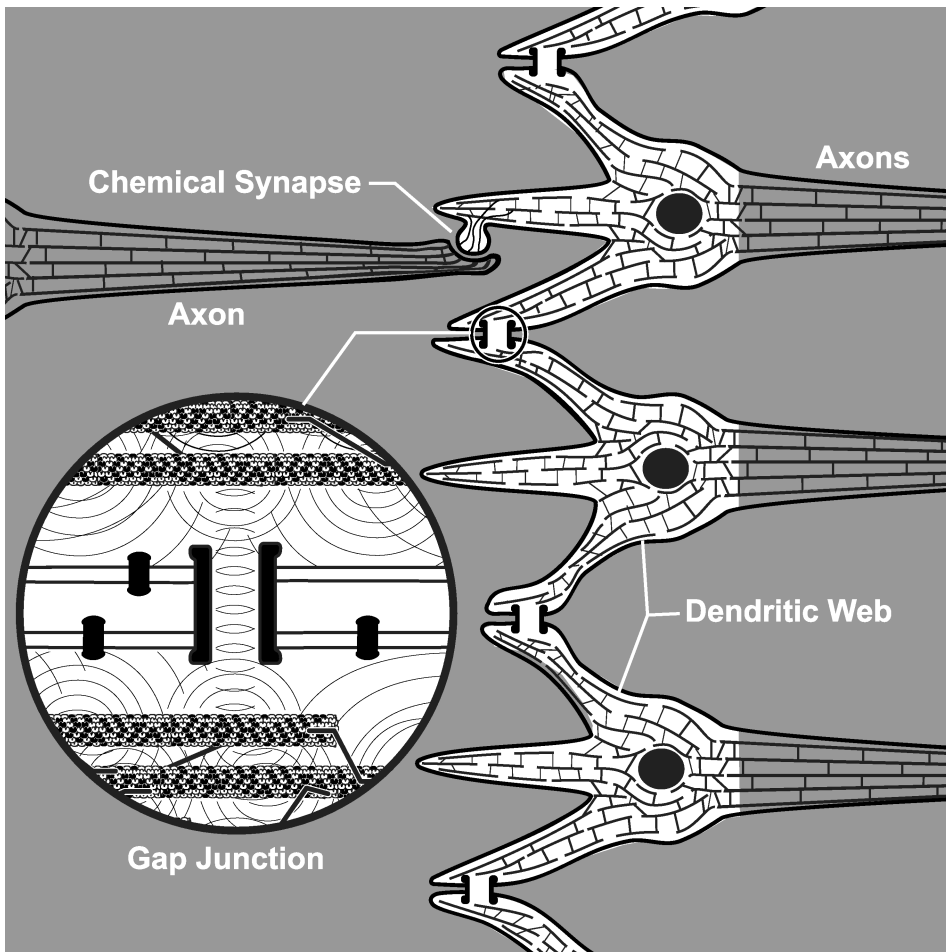


Fig. 1. Dendrites and cell bodies of schematic neurons connected by dendritic–dendritic gap junctions form a laterally connected input layer (dendritic web) within a neurocomputational architecture. Dendritic web dynamics are temporally coupled to gamma synchrony EEG and correspond with integration phases of “integrate-and-fire” cycles. Axonal firings provide input to, and output from, integration phases (only 1 input, and 3 output axons are shown). Cell bodies/soma contain nuclei shown as black circles; microtubule networks pervade the cytoplasm. According to the Orch OR theory, gamma EEG-synchronized integration phases include quantum computations in microtubule networks that culminate with conscious moments. Insert close-up shows a gap junction through which microtubule quantum states entangle among different neurons, enabling macroscopic quantum states in dendritic webs extending throughout cortex and other brain regions.

superpositioned entanglement. The quantum isolated (“integrate”) phases cycle at gamma synchrony frequency with open, communicative (“fire”) phases for inputs to, and outputs from, isolated quantum computations. Quantum states of unconscious possibilities evolve and compute according to the mathematical laws of quantum mechanics until reaching threshold for objective reduction/OR (and a conscious moment) by the indeterminacy principle $E = \hbar/t$. E is the energy/amount of superpositioned mass—for example, the number of quantum superpositioned tubulin proteins, \hbar is Planck’s constant over 2π , and t is the time until OR and

a conscious moment occur. OR events select specific classical output states (e.g., patterns of tubulin protein conformations within dendritic microtubules), which can trigger axonal spikes and govern behavior.

E is also proposed to correlate with intensity of conscious experience. Due to the inverse relation between E and t , large E superpositions (assuming they are isolated/shielded to avoid decoherence) reach threshold quickly (small t , high intensity experience), and small isolated superpositions require long times (small E , large t , low intensity experience). Consequently only in the brain may a sufficiently large number of quantum superpositioned neuronal microtubules be entangled and isolated (in dendritic webs) so that OR/consciousness threshold is reached in relevant time scales. For example setting t equal to 25 msec (duration of one gamma synchrony cycle at 40 Hz), E is equivalent to superpositioned and entangled microtubules in a dendritic web of roughly 100,000 neurons.

Litt et al. ask: “Are we to believe that carrots and rutabagas also exhibit quantum computation, or are conscious?” (p. 597). No, we are not. Plant cells have very few microtubules (very small E); whether they have quantum isolation and quantum computation is unknown. But, assuming they did, by $E = \hbar/t$ a carrot or rutabaga (small E , long t) might have a single, very low intensity conscious moment once per month or so. (Avoiding decoherence for this duration is extremely unlikely.) Apparently high intensity conscious experience (e.g., in meditating Tibetan monks) correlates with extremely high frequency, amplitude and coherence (very high E , low t) of global gamma EEG synchrony (Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004). Orch OR provides consciousness with ontological distinction as sequences of a specific type of physical event—OR-mediated quantum state reductions coupled to neurophysiology.

2.2. Timescale/decoherence

Technological quantum computations apparently require low temperature to avoid “decoherence,” disruption of quantum states by thermal energy in the classical (non-quantum) environment. Decoherence must be avoided long enough for quantum computation to occur (and in Orch OR, for threshold to be reached by $E = \hbar/t$). Thus, many physicists are skeptical of quantum computation occurring in the “warm, wet brain.”

The authors cite Tegmark’s (2000) calculations indicating that microtubule quantum states decohere far too quickly (10^{-13} sec) at brain temperature to exert useful neurophysiological effects. However, Tegmark’s calculations ignored Orch OR stipulations to avoid decoherence. In a footnote, Litt et al. refer to a paper in which we (Hagan, Hameroff, & Tuszyński, 2002) used Tegmark’s decoherence formula with Orch OR stipulations and calculated microtubule decoherence times in hundreds of milliseconds or longer—sufficient for neurophysiological effects. Litt et al. misinterpret those findings, concluding they apply only locally to microtubule subunit proteins—too small a scale to be significant. On the contrary, anti-decoherence stipulations of Orch OR include (a) transiently encasing bundles of dendritic microtubules in actin gel—an isolated, shielded and water-ordered non-liquid environment for quantum processes; (b) quantum states extending among dendritic gel environments via quantum tunneling and/or entanglement through window-like gap junctions of dendritic webs; (c) microtubule quantum error correction topology (Hameroff, Nip, Porter, & Tuszyński, 2002);

and (d) biomolecular quantum states pumped by, rather than disrupted by, heat energy. Indeed, Ouyang & Awschalom (2003) showed that quantum spin transfer through organic biomolecules is enhanced at warm brain temperature. And warm quantum states have recently been demonstrated in semiconductors (Lau et al., 2006; Stern et al., 2006; cf. Amin, Love, & Truncik, 2006).¹

2.3. *Synaptic transmission*

Litt et al. cite philosopher Patricia Churchland, a vocal critic of Orch OR, who said: "... the explanatory vacuum is catastrophic. Pixie dust in the synapses is about as explanatorily powerful as quantum coherence in the microtubules" (Churchland, 1998, p. 597).

(The term "quantum coherence" is vague. We refer specifically to quantum computation involving OR-mediated state reductions of entangled superpositions that we claim provide sequences of discrete conscious moments, e.g., at 40 Hz.)

But, if pixie dust molecules bound to dendritic receptors, how would they differ from neurotransmitters? Where is the explanatory power in neurocomputation? Aspects of mental phenomena should extend to the molecular level (e.g., Thagard, 2002), so the apparent answer lies in specific properties of psychoactive neurotransmitters and their receptors. Recent evidence suggests that interactions between odorant molecules and nasal smell receptor proteins involve not only lock-and-key chemical binding, but also quantum correlations between odorant and receptor molecular electron resonance orbitals (Brookes, Hartoutsiou, Horsfield, & Stoneham, 2006). Potency of hallucinogenic drug molecules correlate with their quantum electron resonance effects on receptors (Kang & Green, 1970; Nichols, 1986; Snyder & Merrill, 1965). Thus, significant quantum correlations may be expected between electron resonance orbitals of psychoactive neurotransmitter molecules (e.g., the indole ring of serotonin, the benzene ring of dopamine, etc.) and their brain receptors.

Litt et al. (2006) cited two Churchland critiques of Orch OR (Churchland, 1998; Grush & Churchland, 1995) but unfairly fail to cite our detailed replies to each (Hameroff, 1998b; Penrose & Hameroff, 1995).

2.4. *Penrose OR is unproven*

The fate of isolated quantum superpositions remains unexplained; Penrose OR (Penrose, 1989, 1994, 1996) is one tentative proposal that is testable, and can also account for consciousness. It is true, as Litt et al. state, that if Penrose OR is proven correct then quantum theory would have to be rewritten. But quantum theory as it stands is incomplete: It *must* be rewritten.

2.5. *Anesthesia*

The authors cite my 1998 paper (Hameroff, 1998a) which proposed quantum London forces in hydrophobic pockets of dendritic brain proteins as the origin for both (a) quantum

states leading to consciousness and (b) anesthetic action. They then stated subsequent work has shown that all anesthetics act on one or more ligand-gated ion channels/receptors, and that my “. . . quantum mechanical theory of anesthesia has been surpassed by biochemical explanations . . .”

My more recent article in *Anesthesiology* (Hameroff, 2006b) points out (a) many drugs bind to these channels/receptors but do not cause anesthesia; (b) anesthetics have varying and confusing effects on channels/receptors (e.g., anesthetics may potentiate excitatory channels and/or inhibit inhibitory channels); (c) within ligand-gated channels/receptors (and other dendritic proteins), anesthetic gases act via quantum London forces in hydrophobic pockets to inhibit electron resonance and thereby selectively prevent consciousness; and (d) anesthetic gas molecules are chemically inert and do not form (bio)chemical bonds with protein targets, acting solely through quantum London forces instead. Thus, to argue that biochemical explanations account for anesthesia is a *non sequitur*.

2.6. Bird flight

The non-dependence of bird flight on quantum effects is irrelevant, because (a) bird flight is understood and consciousness is not, and (b) there is no suggestion of macroscopic quantum states relating to bird flight.

3. The role and function of consciousness

Although Litt et al. did not discuss it, the role and function of consciousness is perhaps the most important question we face. Because evoked potentials and other measurable brain electrical activity correlating with conscious perceptions occur *after* subjects have responded to those perceptions (e.g., Velmans, 1991), neurocomputationalists conclude that consciousness is epiphenomenal and illusory (Dennett, 1991; Dennett & Kinsbourne, 1992; Koch & Crick, 2001; Wegner, 2002). The party line in cognitive neuroscience is that we react unconsciously, after which (1/3 sec behind reality) we construct and falsely remember being and acting in the here and now. “We are merely helpless spectators,” as T. H. Huxley put it. Even unified conscious experience is deemed a mirage (e.g., Dennett, 1991). Maybe so, but evidence suggests backward time effects occur in the brain (e.g., Libet, Wright, Feinstein, & Pearl, 1979). Quantum entanglement apparently depends on seemingly backward time effects which, as unconscious quantum information, can potentially rescue consciousness from the unfortunate position of illusory epiphenomenon (Hameroff, 2006a).

4. Aspects of the brain requiring quantum effects

Litt et al. state “The onus is on those who would appeal to quantum theory to show the existence of aspects of the brain that are not explained by neurocomputational theories, and that can be explained by quantum computation or associated mechanisms” (p. 601).

In my opinion, neurocomputational theories fail to explain essential features of consciousness like binding, transition from unconscious activities to consciousness, non-algorithmic processing and the “hard problem” of subjective experience (Chalmers, 1996). However, these are all arguable.

Instead I point to gamma synchrony electroencephalography (EEG), a candidate for the “neural correlate of consciousness” (the “NCC”). Gamma synchrony EEG (30–90 Hz) has been observed in hundreds of animal and human studies using multi-unit scalp, surface, and implanted electrodes; it occurs within and across cortical areas, hemispheres, thalamus, and even spinal cord (Schoffelen, Oostenveld, & Fries, 2005).

Loss of consciousness associated with onset of general anesthesia is characterized by disappearance of frontal-posterior gamma EEG coherence which returns when patients awaken (Imas, Ropella, Ward, Wood, & Hudetz, 2005; John, 2001; John & Prichep, 2005). During general anesthesia in the absence of consciousness, neurocomputation in the brain continues, evidenced by evoked potentials, sub-gamma EEG, autonomic control, and so forth. For reviews of evidence linking gamma synchrony with consciousness, see Singer (1999) and Hameroff (2006a).

Despite the evidence, gamma synchrony is often questioned as the NCC perhaps because axonal spikes are not coherent (e.g., Koch, 2004; Shadlen & Movshon, 1999). But, in any case, brain-wide gamma synchrony does occur, and is clearly “an aspect of the brain.”

Gamma synchrony involves gap junctions, or electrical synapses—direct open windows between adjacent cells formed by paired collars consisting of classes of proteins called *connexins* (Herve, 2004; Rouach et al., 2002) and *pannexins* (Ray, Zoidi, Weickert, Wahle, & Dermietzel, 2005). Gap junctions occur between brain neuronal dendrites, between axons and axons, between neurons and glia, between glia, and between axons and dendrites—bypassing chemical synapses and electrically coupling neuronal depolarizations (Froes & Menezes, 2002; Fukuda, Kosaka, Singer, & Galuske, 2006; Traub et al., 2002; Traub, Kopell, Bibbig, Buhl, & LeBeau, 2001).

Cortical inhibitory interneurons are particularly studded with gap junctions, potentially connecting each cell to 20 to 50 others (Amitai et al., 2002). Pyramidal cells and other primary neurons have far fewer gap junctions, the numbers decreasing from development to become necessarily sparse (but present; e.g., Ray et al., 2005) in adult primary neurons. Three or more open and active gap junctions per primary neuron (e.g., pyramidal cells, each with thousands of chemical synapses) would cause excessive and dysfunctional coupling.

Dendritic–dendritic gap junction circuits of cortical interneurons and selected primary neurons (in concert with GABA inhibitory chemical synapses) specifically mediate gamma synchrony (Bennett & Zukin, 2004; Buhl, Harris, Hormuzdi, Monyer, & Buzsaki, 2003; Dermietzel, 1998; Draguhn, Traub, Schmitz, & Jefferys, 1998; Friedman & Strowbridge, 2003; Galarreta & Hestrin, 1999; Gibson, Beierlein, & Connors, 1999; Hormuzdi, Filipov, Mitropoulou, Monyer, & Bruzzone, 2004; LeBeau, Traub, Monyer, Whittington, & Buhl, 2003; Perez-Velazquez & Carlen 2000; Rozental, Giaume, & Spray, 2000; Tamas, Buhl, Lorincz, & Somogyi, 2000). Thus, gamma synchrony occurs in the same gap junction-connected dendritic webs within whose cytoplasm Orch OR conscious events are proposed to occur.

While gap junctions are required for gamma synchrony, they still impart some phase delay—that is, gap junctions are necessary but not sufficient to account for the precise global coherence. Recent reviews (Freeman & Vitiello, 2006; cf. John, 2001) concluded that thalamic pacing, recurrent feedback, reciprocal connections, electric fields, and/or gap junction membrane coupling cannot account for precise global coherence of gamma synchrony EEG, and that long range quantum correlations may be required.

Litt et al. and other proponents of neurocomputation should attempt to show how global brain gamma synchrony can be explained by classical (non-quantum) neural mechanisms.

5. Conclusion

Orch OR is a theory of consciousness spanning scale and discipline. It relies on as-yet unproven biology and physics, but is consistent with known science, falsifiable and generates testable predictions (Hameroff, 1998c; Hameroff, 2006a). Orch OR involves quantum computations in microtubule networks embedded within gap junction-linked cortical dendrites (dendritic webs) acting as laterally connected input layers of the brain's neurocomputational architecture. According to Orch OR, consciousness is a sequence of discrete quantum computations, each culminating in a conscious moment in gamma EEG-synchronized integration phases of neurocomputational integrate-and-fire cycles. Orch OR is a specific and viable scientific proposal for consciousness.

Note

1. Biological quantum coherence at significantly warm temperatures has recently been demonstrated in protein scaffolding supporting photosyntheses. See: Engel, Calhoun, Read, Ahn, Mancal, Cheng, Blankenship, & Fleming, 2007.

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