A quantum approach to visual consciousness

Nancy J. Woolf and Stuart R. Hameroff

A theoretical approach relying on quantum computation in microtubules within neurons can potentially resolve the enigmatic features of visual consciousness, but raises other questions. For example, how can delicate quantum states, which in the technological realm demand extreme cold and isolation to avoid environmental 'decoherence', manage to survive in the warm, wet brain? And if such states could survive within neuronal cell interiors, how could quantum states grow to encompass the whole brain? We present a physiological model for visual consciousness that can accommodate brain-wide quantum computation according to the Penrose–Hameroff 'Orch OR' model. In this view, visual consciousness occurs as a series of several-hundred-millisecond epochs, each comprising 'crescendo sequences' of quantum computations occurring at ~40 Hz.

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Conventional neuroscience and cognitive science have been unable to provide a complete account of visual consciousness. Phenomenal or subjective aspects of visual consciousness constituting the 'experience of vision' are the most difficult to explain; indeed, understanding the subjective or experiential aspects of consciousness has been designated as the 'hard problem'[1]. The Penrose–Hameroff ORCHESTRATED OBJECTIVE REDUCTION (ORCH OR) model of QUANTUM computation in MICROTUBULES within neurons can potentially account for subjectivity by connecting the quantum process to a modern form of PAN-PROTOPSYCHIST philosophy[2] (Box 1 and see Glossary). The Orch OR model might also explain other enigmatic features of consciousness including 'binding' or the unitary nature of conscious experience. Regarding binding, we agree with Searle[3] that consciousness is irreducible, and in fact believe that binding requires an actual physical state: QUANTUM COHERENCE. The Orch OR model is also compatible with known neurophysiology and can generate testable predictions[4].

Orch OR and other quantum models have potential explanatory value for the perplexing features of consciousness, but face at least two apparent obstacles. First, technological quantum computation requires isolation and extreme cold to prevent thermal interactions (i.e. DECOHERENCE) that are known to destroy delicate quantum processes[5,6]. Second, it is unclear how a quantum state or field isolated within individual neurons could extend across membranes and anatomical regions to approach brain-wide proportions in *many* neurons. We address the latter issue by postulating QUANTUM TUNNELING across GAP JUNCTIONS, which would allow intracellular quantum states to spread among neurons. We also outline the neuroanatomy and neurophysiology that could accommodate Orch OR and result in phenomenal visual consciousness. First, however, we address the issue of decoherence.

Is quantum computation feasible in the brain?

Orch OR and other quantum models are viewed skeptically for seemingly good reasons. Technological quantum computation requires isolation and extreme cold to avoid rapid decoherence by environmental thermal interactions, yet the brain operates at about 310 K. Quantum states in microtubules within neurons and glial cells would need to be isolated or shielded long enough to reach threshold for Orch OR in neurophysiologically relevant time scales (i.e. ranging from roughly 25 ms to several hundred milliseconds in order to correspond with 'coherent 40 Hz' cognitive epochs[7] and longer time intervals associated with conscious activity[8]). How could quantum isolation or shielding occur in the brain?

The Orch OR model proposes that microtubule QUANTUM SUPERPOSITIONS occur during isolated quantum state phases, which alternate (perhaps at 40 Hz) with classical phases, depending on the state of the cytoplasm of the neuron. The cytoplasm can exist in two phases: solution (Sol) and gelation (Gel), states that are coupled to the polymerization of ACTIN. Sol is a liquid phase in which cytoplasmic actin is depolymerized, thereby enabling microtubules to receive input from, and send output to, the environment (i.e. to communicate with the neuronal membrane). Gel is a solid state phase in which actin densely encases microtubules. In the Gel phase, water on microtubular and actin surfaces becomes ordered, so that water is coupled to the CYTOSKELETON and acts not as environment, but as a shield or part of the quantum system. Furthermore, at physiological pH levels, the terminal amino acids of tubulin extend outward into the cytoplasm bearing negative charges, which attract counter-ion positive charges; this double ion layer forms a plasma phase that can screen microtubule quantum states from decoherence[9].

Based on these mechanisms, decoherence times for microtubule bundles in actin gel have been calculated in the range of hundreds of milliseconds, that is, compatible with neurophysiological processes[10]. Other physical phenomena that might protect microtubule quantum processes include coherent pumping of the cytoplasmic environment[11] and 'quantum error correction' resulting from global topological effects in microtubules, making them impervious to decoherence of individual subunits[12].

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Box 1. Quantum computation, the Orch OR model and conscious experience

Quantum theory describes the bizarre properties of matter and energy at near-atomic scales. These properties include: (1) QUANTUM COHERENCE, in which individual particles yield identity to a collective, unifying wave function (exemplified in Bose–Einstein condensates); (2) non-local QUANTUM ENTANGLEMENT, in which spatially separated particle states are nonetheless connected or related; (3) QUANTUM SUPERPOSITION, in which particles exist in two or more states or locations simultaneously; and (4) QUANTUM STATE REDUCTION or 'collapse of the wave function', in which superpositioned particles reduce or collapse to specific choices. All four quantum properties can be applied to the seemingly inexplicable features of consciousness. First, quantum coherence (e.g. Bose–Einstein condensation) is a possible physical basis for 'binding' or unity of consciousness[a]. Second, non-local entanglements (e.g. 'Einstein–Podolsky–Rosen correlations') serve as a potential basis for associative memory and non-local emotional interpersonal connection. Third, quantum superposition of information provides a basis for preconscious and subconscious processes, dreams and altered states. Lastly, quantum state reduction (quantum computation) serves as a possible physical mechanism for the transition from preconscious processes to consciousness[b,c].

What is quantum computation? In classical computing, binary information is commonly represented as 'bits' of either 1 or 0. In quantum computation, information can exist in quantum superposition, for example, as quantum bits or 'qubits' of both 1 and 0. Qubits interact or compute by entanglement and then reduce or collapse to a solution expressed in classical bits (either 1 or 0). In the Orch OR model, quantum computation occurs in microtubules within the brain's neurons. Microtubules are polymers of the protein tubulin, which in the Orch OR model transiently exist in quantum superposition of two or more conformational states (Fig. I). Following periods of preconscious quantum computation (e.g. on the order of tens to hundreds of milliseconds) tubulin superpositions reduce or 'self-collapse' at an OBJECTIVE THRESHOLD (hence OBJECTIVE REDUCTION) due to a quantum gravity mechanism proposed by Penrose[b,c].

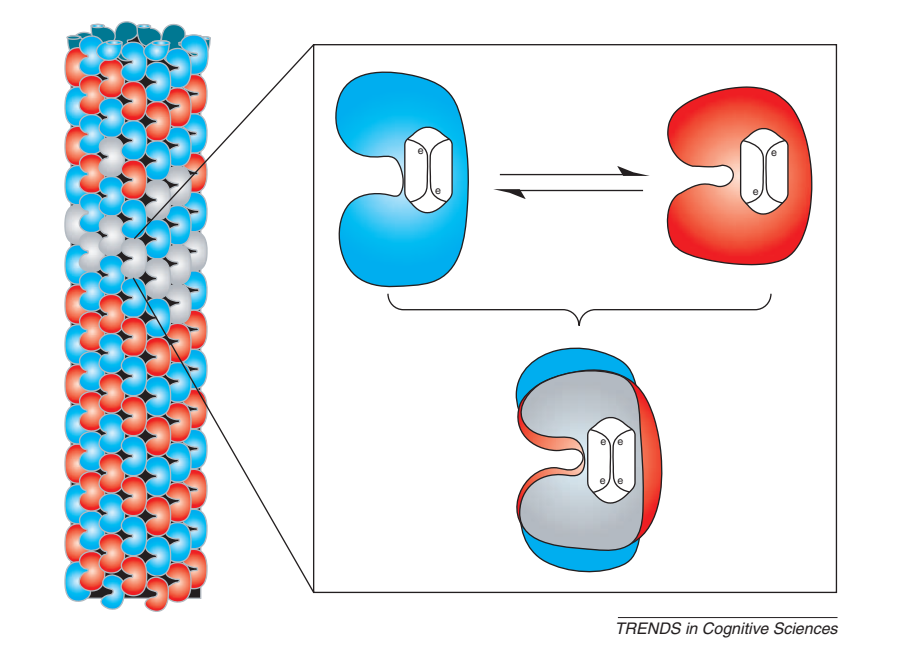

Fig. I. Microtubule structure shown at left: a hollow tube of 25 nm diameter, consisting of 13 columns of tubulin dimers arranged in a skewed hexagonal lattice. Each tubulin molecule can switch between two (or more) conformations (top right: blue, red), coupled to London forces in a hydrophobic pocket. Each tubulin can also exist in quantum superposition of both conformational states (bottom right: gray). According to the Orch OR model, dipole interactions among tubulin states in the microtubule lattice process information classically and by quantum computation.

Microtubule-associated protein (MAP-2) connections provide input during classical phases, thus tuning or 'orchestrating' the quantum computations (hence orchestrated objective reduction or 'Orch OR'). Each Orch OR quantum computation determines classical output states of tubulin, which govern neurophysiological events, such as initiating spikes at the axon hillock, regulating synaptic strengths, forming new MAP-2 attachment sites and gap-junction connections, and establishing starting conditions for the next conscious event[d–g].

These events are suggested to have subjective phenomenal experience (what philosophy calls 'QUALIA') because in the Penrose formulation superpositions are separations in fundamental spacetime geometry. In a pan-protopsychist philosophical view, qualia are embedded in fundamental spacetime geometry and Orch OR processes access and select specific sets of qualia for each conscious event[h].

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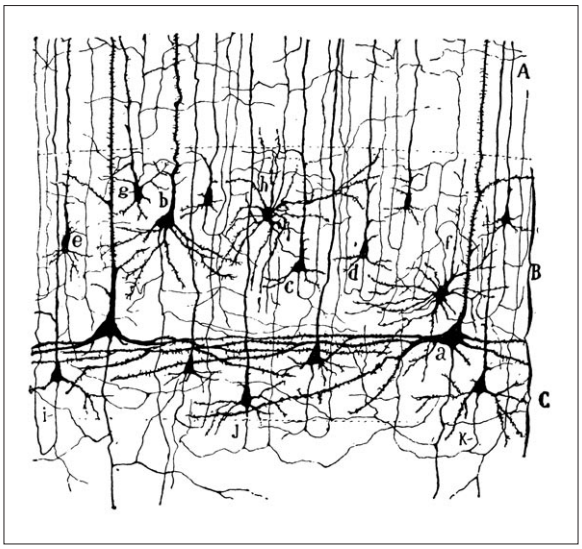

Fig. 1. Cells of the visual cortex (V1) in a 5-year-old child demonstrated by the Golgi method. Reproduced with permission from Ref. 33.

Recent functional magnetic resonance imaging of the brain by 'quantum coherence' makes use of quantum couplings of proton spins in proteins and water, and has revealed a high-resolution neuroanatomical correlate of consciousness[13,14]. Although this type of quantum coherence is induced by the magnetic field produced by the scanner, it shows that significant quantum coherence of some kind can indeed occur in the brain.

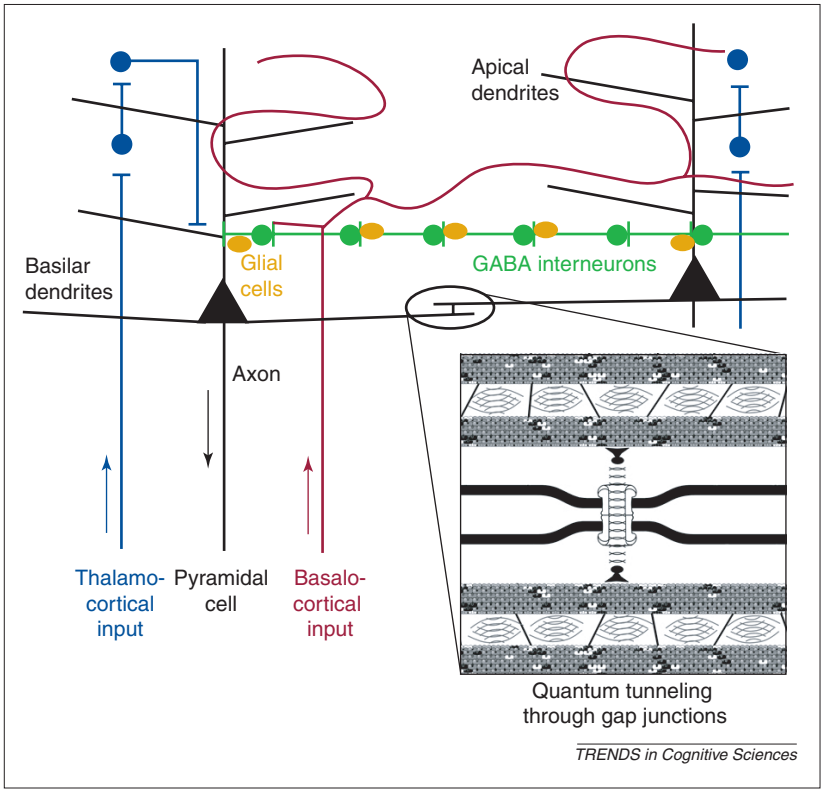

Fig. 2. The basic cortical circuit in consciousness. The pyramidal cell (black) is the central character, receiving thalamocortical (blue) and basalocortical (red) inputs that initiate, respectively, classical and quantum computation. Quantum coherent superposition is entangled among adjacent cortical cells by transient gap junction connections involving (1) basilar dendrites of pyramidal cells (horizontal projections), and (2) gap junctions linking GABA interneurons (green) and glial cells (gold). Inset showing a gap junction between the basilar dendrites illustrates quantum tunneling through the gap junction. This gap junction links two dendritic cytoplasms transmitting coherent quantum activity in the microtubules (wide horizontal bars) tuned by MAP-2 proteins (near vertical lines).

Neuroanatomical and neurophysiological substrates for Orch OR

At the cellular level, the most likely site for Orch OR related to rudimentary visual consciousness is within dendrites and cell bodies of the pyramidal cells in layer 5 of visual cortex (see Fig. 1). Pribram[15] and Eccles[16], among others, have argued that consciousness occurs primarily in dendrites, with axons serving to execute and communicate results of conscious dendritic processes. Pribram[15] emphasized 'horizontal' dendrodendritic connections (e.g. via electrotonic gap junctions) in consciousness. Recently, Logothetis and colleagues have shown that the fMRI signal is more representative of input processing in the dendrites and cell body than of axonal spike outputs[17].

Dendrites in neighboring cells can be directly connected by gap junctions[18]. Membrane depolarizations in neurons connected by gap junction are perfectly synchronous, such that cells connected by gap junctions behave like one giant neuron. Specific gap-junction proteins (i.e. connexins) form collars between each cell's cytoplasmic interior, so neurons or glial cells bound in a gap-junction network share a continuous, common cytoplasm. Such a network constitutes a SYNCYTIUM or what has also been called a 'hyper-neuron'[19].

The Orch OR model suggests that quantum states isolated in the cytoplasmic interior of one neuron can extend to neighboring cells by quantum tunneling across the typically 4-nm gap junctions of neurons (see Fig. 2). Tunneling may be mediated by specific intracellular organelles called 'DENDRITIC LAMELLAR BODIES', which are membrane-covered mitochondria[20]. The specific location and activity of gap junctions and dendritic lamellar bodies within neural processes appear to be regulated by the neuron's microtubule activities. Even though dendrodendritic gap junctions are sparse in comparison with chemical synapses, as few as three gap-junction connections per neuron could weave a transient, widespread syncytium whose unified interior could theoretically host unified quantum states supporting Orch OR through significant brain volumes.

Connections within the 'hyper-neuron'

Three types of input or interconnections within the 'horizontal syncytium' (i.e. gap-junction network) could provide the basis for attention and modulation of Orch OR conscious events in visual cortex (Fig. 2):

(1) Thalamocortical inputs, along with excitatory local circuit cells, relay specific visual information along each vertical column of cortex. These provide non-conscious , neurophysiological information about the visual scene mapped in a point-to-point fashion by GLUTAMATERGIC synapses.

(2) High levels of cortical ACETYLCHOLINE are correlated with increased attention and heightened conscious awareness[21–24]. In our model, inputs from cortical arousal systems, in particular the CHOLINERGIC

Box 2. Linking isolated microtubule quantum computation to neural membrane mechanisms

In our approach, quantum computing by the Orch OR mechanism occurs within pyramidal cell dendritic cytoplasm, but is linked to synaptic membrane events by well-established SECOND MESSENGER chemical cascades activated by METABOTROPIC RECEPTORS (Fig. I). Acetylcholine, operating through the metabotropic muscarinic receptor, serves to activate the second messenger, PHOSPHOINOSITIDE-SPECIFIC PHOSPHOLIPASE C (PI-PLC), which in turn activates two protein kinases: PROTEIN KINASE C (PKC) and CaMK II (Ref. a). These protein kinases then add phosphoryl groups to specific sites on the microtubule-associated protein-2 (MAP-2) molecule. Serotonin, norepinephrine, glutamate and histamine also activate PI-PLC (but to lesser degrees than acetylcholine) via subpopulations of their own metabotropic receptors, leading to additional phosphorylation of MAP-2.

MAP-2 phosphorylation at these particular sites acts to decouple MAP-2 from microtubules and from actin[b–d], the net effect being to isolate microtubules from membrane and environmental influences (Fig. Ib). PI-PLC activation also directly isolates actin molecules from the neuronal membrane[e], further isolating microtubules embedded in actin gel. We suggest that these mechanisms of isolation initiate phases of quantum coherent superposition in microtubules, and then the Orch OR mechanism, resulting in phenomenal consciousness.

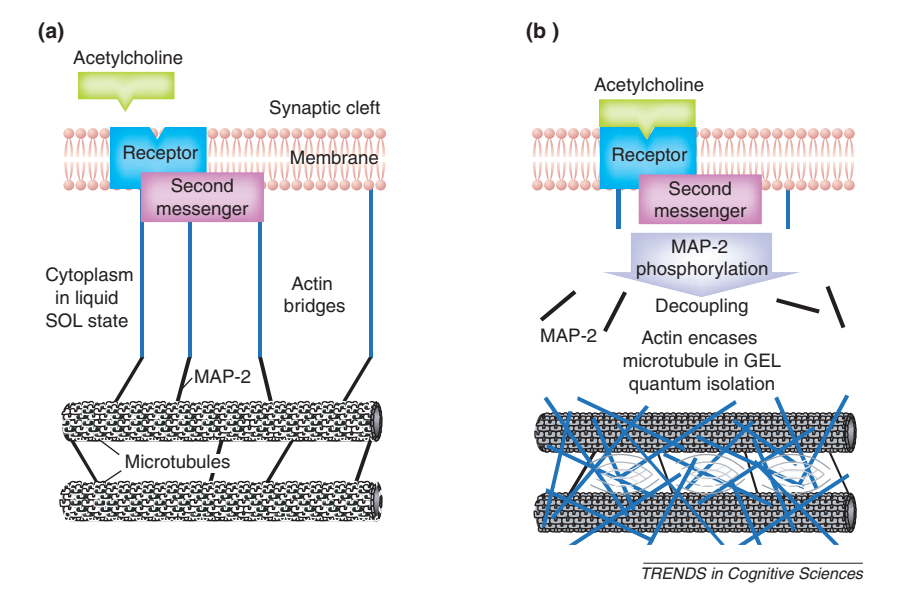

Fig. I. Neuronal cytoplasmic interior switching between (a) classical 'Sol' state, in which membrane and receptors communicate with microtubule information processing, and (b) quantum 'Gel' state in which quantum computations in microtubules are isolated from membrane interactions. Acetylcholine binding to muscarinic receptors (b) acts through second messengers to phosphorylate MAP-2, thereby decoupling microtubules from outside environment. According to our model, such transitions between Sol/classical and Gel/quantum states occur roughly every 25 ms (i.e. around '40 Hz').

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basal forebrain, select content for conscious attention via MUSCARINIC RECEPTOR activation. As discussed more fully below, selection can occur by direct cholinergic actions on pyramidal dendrites, as well as on GABA interneurons.

How could cholinergic activation initiate quantum mechanisms relevant to consciousness? As elaborated in Box 2, muscarinic receptor binding leads to PHOSPHORYLATION of cytoplasmic MICROTUBULE ASSOCIATED PROTEIN-2 (MAP-2) that, in turn, decouples MAP-2 from microtubules via a well-documented chemical cascade. Such decoupling would isolate cytoplasmic microtubules from external influences, serving to minimize environmental decoherence, and in conjunction with actin gelation, enable quantum states leading to Orch OR and ultimately conscious attention.

(3) Coherent cortical oscillations in the EEG gamma frequency (30 – 70 Hz activity, also known in shorthand as '40 Hz') appear to correlate with consciousness[7]. Recent evidence points to inhibitory GABAERGIC cortical interneurons as important mediators of 40-Hz activity[25,26]. The interneurons are themselves connected by gap junctions, and form 'dual' connections with each pyramidal dendrite: an inhibitory GABA chemical synapse and an electrotonic gap-junction connection[27]. GABA interneurons could support Orch OR in three ways: (i) transiently inhibiting cortical membrane activity, thereby minimizing environmental decoherence; (ii) enabling the spread of cytoplasmic quantum states through gap junctions; and (iii) synchronizing brain-wide, coherent 40-Hz activity[28].

Rudimentary visual consciousness

Having examined the underlying neuroanatomy and physiology that could support Orch OR, we now turn to how this mechanism might give rise to visual consciousness. It is generally agreed that ten or more cortical areas are involved in vision and that the main pathway for visual input is from the retina to lateral geniculate of the thalamus and then directly to striate

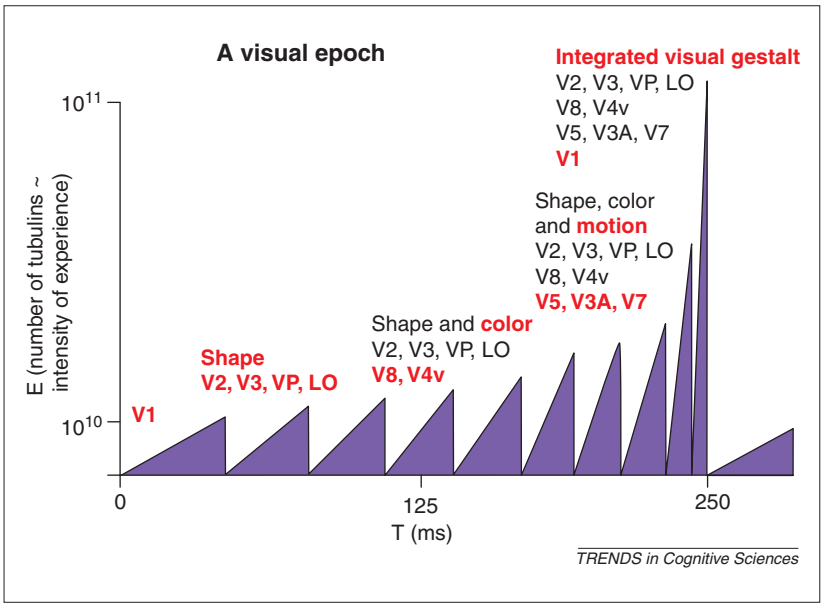

Fig. 3. A crescendo sequence of several ~25 ms quantum computations (i.e. oscillating near to 40 Hz) constitutes a visual epoch lasting 250–700 ms. We propose that a visual gestalt occurs at the end of the epoch as a cumulative function of Orch OR in all the contributing visual areas, including V1. The time until Orch OR (threshold for conscious event) is given by the indeterminacy principle: $E = \hbar / T$ (where E is related to magnitude of the superposition, $\hbar$ is Planck's constant over 2π, and T is the time until self-collapse). Thus the larger the isolated superpositions (higher intensity, more vivid experience) the more quickly they will reduce. Calculations suggest that for T = 25 ms (i.e. time intervals at 40 Hz), E is equivalent to 2×10^{10} tubulins (subunits of microtubules), which occupy roughly 20 000 neurons. For T = 500 ms, E is about 10^9 tubulins, or about 1000 neurons. This implies a spectrum of conscious events of varying intensity and content. Phenomenal consciousness is suggested to correspond to putative and known functional roles of visual areas of cortex[3]. Abbreviations: LO, large-scale object visual cortex; V1–V8, visual areas of cortex; VP, ventral posterior visual cortex.

cortex (V1)[29]. Some neuroscientists believe V1 to be a site for conscious vision; however, many agree with the suggestion of Crick and Koch[30] that conscious vision occurs only in extrastriate cortical areas to which V1 projects because these extrastriate regions connect with frontal regions of cortex (also termed 'executive cortex').

In our view, visual cortex (including V1) is the site of rudimentary visual consciousness, defined here as that which includes only subjective awareness of stimuli present in the visual field (i.e. lines, shapes, colors and motion). We further contend that rudimentary consciousness exists autonomously without strict dependence on 'top-down' influences from 'executive cortex' and other cortical areas, which nonetheless can frame visual consciousness in a particular context or give it semantic meaning. We further speculate that sequences of Orch OR events in various visual areas culminate in a conscious visual gestalt, and that such sequences thereby constitute a physical basis for a moment of rudimentary visual consciousness.

This by no means implies that rudimentary conscious visual experience is simple. Orch OR quantum computing related to specific aspects of visual experience would occur in cortical areas known to process that particular type of information. Thus, familiar object shapes could be identified by Orch OR in V2, V3, VP and LO (see Fig. 3); color in relation to its context could be determined by Orch OR in V4v and V8; and motion detection could occur by Orch OR in V5, V3A and V7. Finally, a visual gestalt is hypothesized to result as a cumulative function of Orch OR in all these visual areas including V1. In this scheme, V1 serves a dual purpose: (1) as a primary recipient of non-conscious neurophysiological visual data, and (2) as a central site for the integrated, selected-for-attention, conscious visual gestalt enabled by quantum coherence and quantum entanglement. Our view of Orch OR events in individual visual cortical regions has certain parallels to the notion of microconsciousness put forward by Zeki and Bartels[31]. Our view also resembles the notion that V1 and V2 act as 'active blackboards' for visual consciousness[32].

Visual consciousness as 'crescendo epochs'

A variety of philosophical and experimental sources – from William James' 'specious moment' to visual saccades to the experimental results of Libet *et al.*[8] – suggest that integrated visual scenes, cognitive events or gestalts are discrete epochs lasting several hundred milliseconds. Yet faster events (e.g. 25 ms events occurring with 40-Hz oscillations) also appear to be important. As shown in Fig. 3, our model accommodates both types of intervals with a 'crescendo sequence' (a sequence of quantum computations of increasing energy) lasting several hundred milliseconds of Orch OR conscious events occurring at roughly 40 Hz (i.e. of average duration 25 ms).

Each Orch OR event within an epoch is of decreasing duration and increasing subjective intensity, culminating with the highest intensity Orch OR event at the end of the epoch. Various aspects of visual information (e.g. shape, color, motion) are integrated into a cumulative visual gestalt at the end of each epoch of several hundred milliseconds, after which another sequence begins. This model can potentially explain aspects of visual consciousness including cognitive and neural responses to illusory figures (see Box 3).

Conclusion

We have presented a seemingly radical model of quantum computation in visual cortex to address the exceedingly difficult features of visual consciousness. According to the Orch OR model, subjective, phenomenal conscious vision depends on quantum computation in microtubules. We have outlined explanations of how quantum states can occur at the temperatures at which the brain operates, and remain stable for time periods commensurate with neurophysiological events. We propose that quantum states supporting Orch OR are isolated in cytoplasmic interiors of cortical pyramidal dendrites interconnected by gap junctions, forming a horizontal

Box 3. Quantum memory: the missing information in Kanizsa figures

Illusory figures with missing edges were designed by Gestalt psychologist Gaetano Kanizsa[a]. Observers routinely fill in the missing sides and perceive full geometric objects (Fig. I). Although these illusions have been widely studied, the mechanism by which the brain generates the missing information and perceives the whole figure is still unclear. Conventional models propose that the missing information is classically computed from memory, mimicking sensory-based, 'bottom-up' sources, or from explicit instructions from 'top-down' sources. We propose that the missing information is derived from memory via quantum computations and quantum entanglements wholly in visual cortex.

In this view, the missing lines or edges in the Kanizsa figure are reconstructed from previous experience, stored in memory as specific architectural arrangements of dendritic microtubule-MAP-2 connections. MAP-2 couplings are altered by learning and memory[b,c], hence tuning or 'orchestration' by the MAP-2 molecule could revive earlier patterns and retrieve relevant memory as part of the conscious event. Upon observation of the incomplete figure, multiple entangled patterns are activated resulting in quantum superposition of all possible complete patterns. On reaching threshold for self-collapse (Orch OR), one particular pattern, usually the most typical shape, is chosen to be a conscious component early in the visual epoch.

PET and fMRI studies indicate that Kanizsa figures having illusory contours mainly activate V1 and V2 (in a similar fashion to figures having real contours), but do not activate frontal cortex[c–f]. In the macaque, electrophysiological responses to illusory contours appear only in V2, not in V1 (Refs g,h); moreover, in a human PET study, Larsson *et al.* showed coupling of V1 and V2 activity with real contours, but decoupling with illusory contours[d]. Consistent with these experimental results, which do not implicate V1 (bottom-up) or frontal cortex (top-down) as sources, our model predicts that quantum computations are the source of those neurophysiological responses to illusory contours in V2. Quantum computations in V2 would then be transmitted to other areas of visual cortex, including V1, through transient entanglements (as described in Box 1 and in the main text). This last prediction is consistent with optical imaging studies showing that activity in V1 varies with the perception as opposed to the physical properties of the stimulus[i].

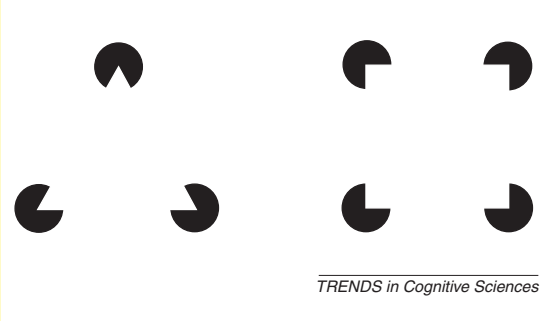

Fig. I. Kanizsa figures have missing sides that are implied by 'pac-man'-like corners. The theory we have outlined proposes that the missing information is derived from memory via quantum computations and quantum entanglements in visual cortex.

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network or syncytium spanning visual cortical regions. Isolated quantum phases alternate with classical phases at approximately 40 Hz, the frequency that has been associated with synchronized cortical activity underlying conscious states. The horizontal networks are driven by non-conscious thalamocortical inputs, as well as by basal forebrain cholinergic inputs that select (along with 'top-down' mechanisms) particular content for conscious attention. Quantum computation might be the future of information technology, and as with current computer technology, comparisons to brain functioning will be inevitable. We believe that they will also be valid.

Questions for future research

- How are certain objects or aspects of a visual scene selected for attention?
- How is it that inputs from different parts of the visual field, as well as visual inputs arriving at different times, are globally integrated into unitary visual objects and scenes (spatial and temporal binding)?
- What are the neural and physical mechanisms whereby objects and scenes become subjectively conscious, and what exactly is phenomenal visual consciousness (the 'hard problem' of phenomenal vision)?

Glossary

acetylcholine: a neurotransmitter found in the peripheral and central nervous systems required for movement, memory, attention and consciousness.
actin: filamentous cytoskeletal protein, which polymerizes to form cytoplasmic gel.
CaMK II: (calcium/calmodulin-dependent kinase II) a protein molecule that adds phosphoryl groups to other molecules as a mechanism of activation.
cholinergic: an action or neuronal system utilizing acetylcholine.
cytoskeleton: the internal scaffolding (microtubules, MAP-2, actin, etc.) within cells.
decoherence: loss of quantum coherence, due to environmental interactions that breach isolation.
dendritic lamellar bodies: organelles containing mitochondria situated adjacent to gap junctions between neighboring dendrites.
GABA: (gamma-aminobutyric acid) a widespread inhibitory neurotransmitter.
GABAergic: an action or neuronal system utilizing the neurotransmitter GABA.
gap junctions: pore-like linkages between two or more cells, including neurons.
glutamatergic: an action or neuronal system utilizing the neurotransmitter glutamate.
MAP-2: (microtubule-associated protein-2) a high molecular weight protein that interconnects microtubules with each other and with actin.
metabotropic receptors: postsynaptic receptors that respond to neurotransmitter binding by activating second messenger cascades and influencing cytoplasmic dynamics.
microtubules: assemblies of tubulin in hollow cylindrical structures found inside neurons.
muscarinic receptor: a metabotropic acetylcholine receptor found in the central nervous system.
objective reduction: collapse of the quantum wave function or superpositioned states, due to an objective threshold.
objective threshold: a physical factor causing quantum state reduction (e.g. the Penrose quantum gravity factor given by the indeterminacy principle: $E = \hbar/T$).
Orch OR: (orchestrated objective reduction) the Penrose–Hameroff model of consciousness that describes reduction or collapse of superpositioned states in tubulin molecules (found in the microtubules of neurons) due to the Penrose quantum gravity threshold and its fine-tuning (orchestration), for example, by MAP-2.
pan-protopsychist: a philosophical approach embracing the notion that the subjective or phenomenal properties of mind (i.e. qualia) are fundamental irreducible components of the universe, analogous to spin, charge or spacetime geometry (i.e. quantum gravity).
phosphoinositide-specific phospholipase C: (PI-PLC) a second messenger that mediates subsequent chemical responses in the nerve cell.
phosphorylation: the process of adding a phosphoryl group to a molecule, usually as a mechanism to activate that molecule.
protein kinase C: (PKC) a protein molecule that phosphorylates other molecules as an activating mechanism inside cells.
qualia: philosophical term that refers to raw components of subjective, phenomenal, conscious experience (e.g. what it is like to see red).
quantum: (1) the smallest quantity of radiant energy, equal to Planck's constant multiplied by the frequency of the associated radiation; (2) the scale at which matter and energy interact (e.g. quantum coherence, c.f.).
quantum coherence: quantum state in which components are governed by a single wave function and are essentially one common entity.
quantum entanglement: non-local, instantaneous connection between previously coupled quantum entities, for example, Einstein–Podolsky–Rosen pairs in which measurement of one member of the pair instantaneously 'collapses' or reduces its opposite member regardless of location (referred to by Einstein as 'spooky action at a distance').
quantum state reduction: 'collapse of the wave function', in which superpositioned particles reduce or collapse to specific choices
quantum superposition: quantum states in which particles or energy exist in multiple locations or states simultaneously.
quantum tunneling: translocation of quantum particles through energy and physical barriers.
second messengers: molecules that carry out chemical responses inside nerve cells (e.g. PI-PLC).
syncytium: a network of cells woven together by gap junctions to form a common cytoplasmic interior.

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