Review

Consciousness, biology and quantum hypotheses

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Abstract

Natural phenomena are reducible to quantum events in principle, but quantum mechanics does not always provide the best level of analysis. The many-body problem, chaotic avalanches, materials properties, biological organisms, and weather systems are better addressed at higher levels.

Animals are highly organized, goal-directed, adaptive, selectionist, information-preserving, functionally redundant, multicellular, quasi-autonomous, highly mobile, reproducing, dissipative systems that conserve many fundamental features over remarkably long periods of time at the species level. Animal brains consist of massive, layered networks of specialized signaling cells with 10,000 communication points per cell, and interacting up to 1000 Hz. Neurons begin to divide and differentiate very early in gestation, and continue to develop until middle age.

Waking brains operate far from thermodynamic equilibrium under delicate homeostatic control, making them extremely sensitive to a range of physical and chemical stimuli, highly adaptive, and able to produce a remarkable range of goal-relevant actions.

Consciousness is "a difference that makes a difference" at the level of massive neuronal interactions in the most parallel-interactive anatomical structure of the mammalian brain, the cortico-thalamic (C-T) system. Other brain structures are not established to result in direct conscious experiences, at least in humans. However, indirect extra-cortical influences on the C-T system are pervasive. Learning, brain plasticity and major life adaptations may require conscious cognition.

While brains evolved over hundreds of millions of years, and individual brains grow over months, years and decades, conscious events appear to have a duty cycle of ∼100 ms, fading after a few seconds. They can of course be refreshed by inner rehearsal, re-visualization, or attending to recurrent stimulus sources.

These very distinctive brain events are needed when animals seek out and cope with new, unpredictable and highly valued life events, such as evading predators, gathering critical information, seeking mates and hunting prey. Attentional selection of conscious events can be observed behaviorally in animals showing coordinated receptor orienting, flexible responding, alertness, emotional reactions, seeking, motivation and curiosity, as well as behavioral surprise and cortical and autonomic arousal. Brain events corresponding to attentional selection are prominent and widespread. Attention generally results in conscious experiences, which may be needed to recruit widespread processing resources in the brain.

Many neuronal processes never become conscious, such as the balance system of the inner ear. An air traveler may "see" the passenger cabin tilt downward as the plane tilts to descend for a landing. That visual experience occurs even at night, when the traveler has no external frame of spatial reference. The passenger's body tilt with respect to gravity is detected unconsciously via the hair cells of the vestibular canals, which act as liquid accelerometers. However, that sensory activity is not experienced directly.

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It only becomes conscious via vision and the body senses. The vestibular sense is therefore quite different from visual perception, which "reports" accurately to a conscious field of experience, so that we can point accurately to a bright star on a dark night. Vestibular input is also precise but unconscious.

Conscious cognition is therefore a distinct kind of brain event. Many of its features are well established, and must be accounted for by any adequate theory. No non-biological examples are known.

Penrose and Hameroff have proposed that consciousness may be viewed as a fundamental problem in quantum physics. Specifically, their 'orchestrated objective reduction' (Orch-OR) hypothesis posits that conscious states arise from quantum computations in the microtubules of neurons. However, a number of microtubule-associated proteins are found in both plant and animal cells (like neurons) and plants are not generally considered to be conscious.

Current quantum-level proposals do not explain the prominent empirical features of consciousness. Notably, they do not distinguish between closely matched conscious and unconscious brain events, as cognitive-biological theories must. About half of the human brain does not support conscious contents directly, yet neurons in these "unconscious" brain regions contain large numbers of microtubules.

QM phenomena are famously observer-dependent, but to the best of our knowledge it has not been shown that they require a *conscious* observer, as opposed to a particle detector. Conscious humans cannot detect quantum events "as such" without the aid of special instrumentation. Instead, we categorize the wavelengths of light into conscious sensory events that neglect their quantum mechanical properties.

In science the burden of proof is on the proposer, and this burden has not yet been met by quantum-level proposals. While in the future we may discover quantum effects that bear distinctively on conscious cognition 'as such,' we do not have such evidence today.

1. Introduction

The human brain supports a variety of structures and processes that are allow us to compare "conscious version unconscious" information processing. These two kinds of brain events are strikingly different, but they interact seamlessly. Most obviously, we have the capacity to report conscious brain events, sometimes with remarkably accuracy; no such capacity exists for the half of the brain (very roughly) that does not yield direct conscious events. However, there is now a sizable body of brain and behavioral evidence that differentiates reliably between conscious and unconscious aspects of the brain [11].

Conscious events are commonly assessed by accurate reports of sensory stimuli and basic cognitive tasks, while unconscious ones are inferred when there is strong evidence for neuronal information processing without reportability [1]. While accurate report has long been used in sensory psychophysics and a variety of medical conditions (like coma and seizures), researchers constantly seek better measures. Significant progress toward better brain indices has been made in recent years [23].

Some of the most useful evidence compares closely matched conscious and unconscious brain phenomena. Binocular rivalry is one well-studied technique to compare optically identical retinal stimuli that cannot be fused into a single, consistent, conscious percept. Thus one of the two inconsistent input streams is unconscious at any given moment. At least a dozen other experimental paradigms allow for such comparisons. Theoretical ideas are therefore strongly constrained by a growing body of evidence.

A variety of brain measures converge on the conclusion that the cerebral cortex and its major input hub, the thalamus, are strongly implicated in specific conscious experiences. Damage to the thalamus and cortex impairs conscious functions, sometimes as a state (e.g., deep sleep and coma), and sometimes in specific conscious contents (blindsight, hemineglect, cortical color blindness). Thus, very small lesions in the color area of the visual cortex (area V3/V4) may abolish the conscious perception of red objects, but not their unconscious identification [31]. Similarly, damage to the first cortical map of the visual pathway (area V1) blocks conscious vision, but not unconscious or "near-unconscious" vision. Thus we see the remarkable condition of 'blindsight,' in which patients deny having visual experiences at all, but can still walk through a hallway without bumping into scattered chairs and tables.

Many structures outside of the human cortex and thalamus do not support moment-to-moment conscious contents, though they constantly interact with cortex. Generations of medical students have learned that the two large cerebellar

lobes can be massively damaged without significantly impairing the conscious state or its stream of momentary contents [2]. Cerebellum and cortex have similar numbers of neurons, although they differ in cellular morphology and in patterns of connectivity. The cerebellum is thought to involve a large set of parallel modules, analogous to a computer server farm. In contrast, cortex and thalamus constitute a vast parallel-interactive nexus that follows plausible network mathematics.

However, the structural connectivity of the C-T system is not enough, since moment-to-moment brain functions require dynamic flows of signal traffic among many brain regions, perhaps at multiple spatial and temporal scales.

Based on a large number of animal studies, Steriade proposed that

"The cerebral cortex and thalamus constitute a unified oscillatory machine displaying different spontaneous rhythms that are dependent on the behavioral state of vigilance." (I.e., waking, deep sleep, and dreaming.)

This view is widely accepted. The oscillatory activity of the waking state depends on small driving circuits, which are controlled by chemical modulation from basal brain nuclei [28]. These switching circuits are delicately tuned to the circadian cycle.

In the oscillatory ocean of the waking C-T system, specific types of information processing appear to involve phase-locking among task-specific regions of the cortex, thalamus, and satellite regions like the basal ganglia. A hierarchy of waveforms is believed to be involved, ranging from slow oscillations (<1.0 Hz) to high gamma (perhaps 120 Hz, with bursts up to 600 Hz). Phase-locking occurs both within and between frequency ranges like theta (4–7 Hz) and gamma (25–200 Hz). Phase asynchrony has also been proposed to play a role. Even single neurons may lock their spike firing patterns to regional theta activity [7]. Such a self-organizing capability among large numbers of neurons allows for widespread recruitment of cortical resources to accomplish survival tasks.

The neural code or codes of the brain are not completely known, but they appear to involve both spatial and time–frequency coding. Sensory and motor cortices consist of layered arrays of cells that often preserve spatiotopical consistency from array to array. Thus the first visual 'map' of the cortex (area V1) corresponds point-to-point both to the retina and the visual thalamus. Cortex and thalamus are massively interconnected via bidirectional pathways linking functionally specific neuronal arrays. Since the cortex is now believed to have approximately 1000 functionally different areas (Brodmann areas), the potential for interactive processing is very large indeed.

Theta oscillations of 4–7 Hz have multiple sources in the brain, and may constitute a common "carrier wave" for higher-frequency oscillations. In the case of episodic memory (memory for conscious events) theta oscillations play a major role in high-fidelity information transmission between hippocampus and neocortex. Under optimal conditions, memories of conscious events are remarkably accurate, suggesting that conscious moments may trigger very high-resolution memory coding and retrieval.

A large variety of oscillatory phenomena have been observed in the brain, including traveling and standing waves, vortices and even interference patterns. Both Fourier and Hilbert analyses reveal major regularities in the wave activities of the cortex [13]. At a microscopic level, neuronal spike timing is known to shape synaptic plasticity. These findings suggest a very rich spatiotemporal coding repertoire, which may be different in different brain regions.

Even at the gross anatomical level the C-T system looks like a massive parallel-interactive system. It seems optimized for flexible, interactive, and multi-functional adaptations, while the equally large cerebellar lobes are specialized for faster, more predictable and modular tasks.

The basal ganglia, one of the major output hubs of the C-T system, again appear to function as a more parallel and modular system, which does not give rise to conscious experiences "as such."

No currently known quantum-level phenomena account for the striking differences between conscious versus non-conscious brain events. If conscious cognition depended on quantum computation in microtubules we would expect all parts of the brain to be conscious, since all cells are richly endowed with microtubules. Indeed, plant microtubules have many proteins in common with cortical ones [14].

1.1. Quantum observer effects

It is often said that the conscious brain may cast light on quantum observer effects. However, it is not clear that those effects necessarily involve conscious observation; if electronic instruments can record particle momentum and

location, presumably the quantum waveform would collapse without consciousness. There is no reason to think that electronic instruments are conscious. Complex information processing can occur in the human brain and in artificial systems without consciousness. By itself, complex processing therefore does not require conscious cognition. Biologically, complex neuronal information processing is extremely widespread, ranging from insects to cephalopods.

While quantum theory has not been shown to bear distinctively on the neurobiology of consciousness, physics provides important theoretical tools for understanding the brain, as in the growing understanding of complex systems, network theory, systems of loosely coupled oscillators, and non-linear dynamics.

2. Evidence bearing on consciousness

Subjectively, consciousness is the water in which we swim. We cannot compare conscious and unconscious events introspectively, because when we lose consciousness we also lose the ability to observe. Historically, gravity was equally difficult for scientists to study, because comparison conditions were hard to find. Without astronomical evidence, degrees of gravitational force were difficult to measure.

Baars has argued that the crucial scientific question is, "what are the observable differences between closely matched conscious and unconscious brain events?" [1,4]. The behavioral index of consciousness is "accurate, voluntary report." While this is a common sense index, it has been used in the sensory sciences for two centuries. We are now beginning find improved brain indexes for conditions like coma and epilepsy [23].

To study consciousness as a variable of interest it is often useful to compare physically identical stimuli flowing into identical receptor arrays, like the two retinas. This helps us to focus on variables that bear directly on consciousness 'as such.' Such experiments pose no philosophical puzzles, since both experimental conditions are indisputably physical. 'Contrastive analysis' experiments have now led to a large research literature. The biomedical database PubMed cites more than 30,000 articles for 'consciousness.'

Table 1 summarizes seventeen well-established features, each with its own research literature.

2.1. A difference that makes a difference

An adequate conception of consciousness must explain why it is a difference that makes a difference. Consciousness is not some non-physical cloud that hovers above the head, though some have thought so. Rather, conscious mentation is critically dependent upon a specific part of the brain, the giant cortex and its major input hub, the thalamus; but only when these organs "constitute a unified oscillatory machine displaying different spontaneous rhythms ..." that can represent stimulus information (perception), encode that information in episodic memory, utilize it to made decisions and resolve conflicting inputs and outputs, selectively attend to some but not other types of information from external and internal sources, assess different goals, and after suitable evaluation, take effective action choices that serve the organism in its Darwinian fitness functions. Although sleep and dreaming have their own biological functions, as we can tell by their large repertoire of associated epigenetic functions, they do not support conscious perception, episodic memory acquisition, careful judgment and decision making, and effective action control and execution.

What is the physiological difference between conscious and unconscious states? What differentiates the conscious and unconscious stream in binocular rivalry? How does the brain differentiate between novel and more conscious tasks compared to routine and less conscious ones?

Some have argued that consciousness depends upon sub-cellular quantum phenomena, perhaps involving state changes in microtubules, which are critical cytoskeletal components of neurons. However, quantum-level events pervade both conscious and unconscious brain conditions. To date, there is no evidence for differential effects of quantum activity in conscious brain events.

Moreover, microtubules and ion channels are pervasive in both the C-T system and the cerebellum and brain stem, as well as in virtually all eukaryotic cells outside of the nervous system, and, indeed, even in plant cells.

The conscious state and its contents therefore appear to reflect a major biological adaptation. At this time, there is no evidence that quantum-level phenomena differentiate between conscious and unconscious brain events. Quantum phenomena must necessarily occur in animal and plant tissue, but they do not present a difference that makes a difference with respect to conscious cognition.

Table 1
Major features of consciousness.

EEG signature of conscious states.
Irregular, low-amplitude, and fast electrical activity in the gross electrophysiological activity of the brain, ranging from 0.5 to 400 Hz. Conscious EEG looks markedly different from unconscious states—like deep sleep, epileptic loss of consciousness and general anesthesia—which show regular, high-amplitude, and slow voltages.

Cortex and thalamus.
Consciousness depends on the cortico-thalamic complex, turned on and off by brainstem neuromodulation, and interacting with subcortical regions that do not support conscious experiences directly.

Widespread brain activity.
Reportable conscious events are associated with widespread content-specific brain activity. Unconscious stimulation evokes only local cortical activity. Conscious moments also trigger wide effects outside the focus of current conscious contents, as indicated by implicit learning, episodic memory, biofeedback training and the like.

Wide range of reportable contents.
Consciousness has an extraordinary range of different contents—perception in the various senses, endogenous imagery, emotional feelings, inner speech, concepts, action-related ideas and "fringe" experiences such as feelings of familiarity.

Informativeness.
Consciousness may fade when signals become redundant; a loss of information may also lead to a loss of conscious access. Studies of selective attention also show a strong preference for more informative conscious stimuli.

The adaptive and fleeting nature of conscious events.
Immediate experience of sensory input may last up to a few seconds, and our fleeting cognitive present is surely less than half a minute. In contrast, vast bodies of unconscious knowledge reside in long-term memory.

Internal consistency.
Consciousness is marked by a consistency constraint. In general, of two mutually inconsistent stimuli given simultaneously, only one can become conscious. While multiple meanings of common words are believed to be active for a brief time, only one becomes conscious at any moment.

Limited capacity and seriality.
The capacity of consciousness at any given moment seems limited to one consistent scene. The flow of such conscious scenes is serial, in contrast with the massive parallelism of the brain when it is observed directly at the same time.

Sensory binding.
The sensory brain is functionally fragmented, such that different cortical areas are specialized to respond to different features such as shape, color, or object motion. One fundamental question is how these functionally segregated regions coordinate their activities to generate the integrated gestalts of ordinary conscious perception.

Self-attribution.
Conscious experiences are always attributed to an experiencing self, the "observing ego," as William James called it. Self functions appear to be associated with midline brain regions, including brainstem, precuneus and orbitofrontal cortex in humans.

Accurate reportability.
The most used behavioral index of consciousness is accurate reportability. The full range of conscious contents are reportable by a wide range of voluntary responses, often with very high accuracy. Reportability does not require a perfectly explicit vocabulary, since subjects can voluntarily compare, contrast, point to, and act upon conscious events.

Subjectivity.
Consciousness is marked by a private flow of events available only to the experiencing subject. Such privacy violates no physical laws. This suggests that self-object integration is a key to conscious cognition.

Focus-fringe structure.
While consciousness tends to be thought of as a focal, clearly articulated set of contents, "fringe conscious" events, like feelings of familiarity, the tip-of-the-tongue experience, intuitions, etc., are equally important.

Facilitation of learning.
There is little evidence for significant learning without consciousness. In contrast, the evidence that conscious experiences facilitate learning is overwhelming. Even implicit (indirect) learning requires conscious attention.

Stability of contents.
Conscious contents are impressively stable, given the variability of input and task demands, such as the eye-movements that readers constantly use to scan sentences. Even abstract conscious contents like beliefs, concepts, and aspects of oneself can be remarkably stable over decades.

Table 1 (*Continued*)

Allocentric attribution.
Conscious scenes and objects, generally speaking, are attributed to external (allocentric) sources, though they are heavily shaped by unconscious frameworks.

Conscious knowing and decision-making.
Consciousness is useful for knowing the world around us, as well as some of our own internal processes. Conscious representations, including percepts, concepts, judgments and beliefs, may be particularly suited for voluntary decision making. However, all conscious events involve a vast unconscious infrastructure. Thus the reportable contents of consciousness are by no means the only feature that needs to be explained.

3. Biologically-inspired proposals

Theoretical concepts from physics often provide important insights into brain functions, both conscious and unconscious [11,27,30]. For example, the cells of cortex and thalamus are linked by 'small world networks' of axons and synapses [25]. As mentioned earlier, the cerebellum has a comparable number of cells to cortex, but its connectivity is parallel and modular. This is consistent with a body of evidence indicating that the cerebellum does not support conscious contents directly [5], though it interacts at high rates with cortico-thalamic regions that do.

The cortex is thought to maintain a far-from-equilibrium dynamical state during waking, one that is different from unconscious states like deep sleep, epileptic loss of consciousness, and coma [3,12,29]. Slow-wave sleep, the least conscious of all neural states in mammals, is dominated by slow (<4 Hz), high-amplitude, and synchronous field potentials in the cortex and thalamus. Since the cells of this system not vary much across global states, it is their mass oscillatory activity that makes the difference between slow-wave sleep and waking. During slow-wave sleep, cortical neurons do not slow their average firing rates. Rather they tend to fire and pause in coherent "buzz–pause" cycles at 1–4 Hz. Slow-wave sleep facilitates consolidation of information learned during the preceding conscious period [2].

During deep sleep, the simultaneous pausing of billions of neurons appears to momentarily block task-related processing. By comparison, waking shows fast, uninterrupted, task-sensitive interactions among tens of billions of neurons engaged in transient phase-locking and desynchronization in the theta-to-high-gamma range. This appears to be crucial difference between waking and deep sleep.

Similarly, in epileptic seizures, it is the slow, high-amplitude, massive on-off activity that is experienced as a loss of consciousness. Epileptic loss of consciousness during seizures resembles slow-wave sleep, and thus interferes with normal survival tasks.

Loss of consciousness can also be induced chemically or mechanically (e.g., by a blow to the jaw), but this does not mean that consciousness is best explained either by purely molecular or large-scale skeletal mechanisms. For consciousness, the crucial level of analysis appears to be the mass interactions among billions of cells in the C-T system.

Consciousness appears to be a major biological adaptation. The EEG of waking and sleep is highly conserved in vertebrates. The sleep–waking cycle triggers gene expression for hundreds of different neuronal genes, perhaps for the purpose of learning (during waking) and memory consolidation (during slow-wave sleep). Its evolution occurred over more than 200 million years in mammals and probably birds. There is now an emerging literature in cephalopods suggesting that invertebrates, who diverged from vertebrates some 600 million years ago, may have homologous states, corresponding to their externally observable brain states. This scientific literature is in an early stage of development, but if that hypothesis receives adequate support it may be that consciousness and its loss goes back to an early common ancestor, or that, like the lensed eye, it evolved more than once in the very long course of multicellular evolution.

4. Primary vs. higher-order consciousness

Edelman makes a distinction between primary (sensorimotor) and higher-order (symbolic, abstract, and language-dependent) consciousness. This distinction has been made from early in intellectual history, but the terminology of "primary" vs. "higher-order" is a useful one in a biological and paleoanthropological context.

Higher-order consciousness in hominins (the current preferred term for human-like species) likely emerged much later than primary consciousness, perhaps as recently as 100,000 years ago, compared to hundreds of millions of years for mammalian and pre-mammalian sensorimotor consciousness. Its emergence was likely associated with the appearance of full-fledged language, music, symbolic, group dance, flexible tool-making, and symbolic culture in

general. Higher-order consciousness is the precondition for the explosion of technologies and large cultures over the past six millennia.

These facts can be studied at many levels of analysis, ranging from molecules to visible behavior. However, we have no direct evidence for quantum-mechanical processes making a difference between conscious and unconscious brain events.

5. What's different about the waking state?

The far-from-equilibrium dynamics of the waking state support rapid adaptivity to new and highly-valued events, a prominent feature of conscious perception and cognition. Waking is the main time for information intake, and generates a very large, flexible, and goal-directed behavioral repertoire. Almost any C-T neuron can come under delicate voluntary control, using almost any conscious feedback signal for training (e.g. [1]). This ability to associate almost any conscious stimulus with almost any neuronal activity is an index of the remarkable interactive selectivity of the C-T core.

Although the fast and flexible oscillatory dynamics of the C-T system makes it potentially unstable, homeostasis is thought to be maintained by large numbers of inhibitory GABA synapses, as well as the fact that exogenous stimulation is only a small fraction of C-T activity. The cortex "mostly talks to itself". Conscious stimuli, when compared to unconscious ones, only appear to change observable neuronal activity in brief (100–200 ms) bursts about 300 ms after stimulus onset, and in quantitatively small ways. Neural code(s) are hypothesized to involve fast, oscillatory, cross-frequency phase-locking. Such a code does not have to be thermodynamically large to enable effective signal processing.

The role of REM dreaming is still unclear, but it is widely believed to be a conscious state, both by immediate report criteria when humans are awoken from REM dreams, and by the oscillatory regime of the C-T core, which closely resembles waking.

Sleep and dreaming drastically reduce the sensitivity of cortical and thalamic stimulus processing, and involve inhibition of the large skeletal (voluntary) muscles. These states make animals highly vulnerable, so that they must seek safety in burrows, caves, rock crevasses, in trees, dense underbrush, and in protective social groups. All animals wake up quickly from sleep when sensory input is intense or meaningful. An inability to wake up in response to moderate stimulation indicates a dysfunctional condition like stupor or coma.

6. Consciousness, selectionism, and evolution

Conscious experiences depend upon a number of neural structures and functions, like the C-T core, actuated by state-switching nuclei at the base of the brain. These small nuclei are themselves under delicate timing control, triggered by environmental events like sunlight, dusk, hunger and eating. The sleep–wake cycle and its disruption triggers more than 200 types of gene expression, suggesting that circadian states play numerous biological roles [8].

The structure and dynamics of the C-T system provide a good index for consciousness in mammalian brains, along with distinctive behavioral properties. However, the absence of a visible C-T complex in other species does not exclude consciousness, or something like it. Biology shows many examples of parallel evolution.

All animals evolved from earlier forms. Since the sufficiency conditions of conscious brains are not yet known, we cannot be sure where consciousness begin. Currently we can say that consciousness seems to include the mammals, which have the brain anatomy discussed above. However, this does not exclude analogous phenomena in other species. Birds and cephalopods are currently under active study, while plants do not have specialized fast, long-distance signaling cells like neurons. While artificial conscious systems are conceivable, we believe that current computational efforts are primarily useful as theoretical simulations.

Given the robust biological nature of the neuronal substrates for conscious events, the possibility of a distinctive quantum-mechanical basis seems remote.

7. Parallel evolution

The question is often raised whether extraterrestrial creatures can be consciousness, whether machines can be conscious, and the like. Given our current lack of a deep understanding of consciousness, these questions often seem

premature. However, we have biological examples of complex structures emerging multiple times during evolution, in what appears to be parallel adaptations emerging in very distantly related species under similar genetic pressures.

The appearance of the vertebrate eye can be understood in terms of a sequence of incremental evolutionary stages, from a patch of light-sensitive cells to a fully formed camera eye. The strength of this argument rests on the fact that an analog for each of these stages has been identified in a living organism [17,20]. Moreover, the function of each stage can be understood in terms of known physiological processes. Notably, although vision certainly involves physical interactions of environmental photons with sheets of photoreceptors, everything that happens beyond these interactions that relates to the functional mechanism of vision can be described in molecular, cellular, and physiological terms, and can be understood to have taken shape through natural selection.

In the medial temporal lobe (MTL), a structure that is key to transforming experiences into long-term memories, two kinds of neurons, 'place cells' and 'grid cells,' have been linked to specific aspects of spatial memory and navigation. As a rat explores a maze, place and grid cells fire and become correlated with particular locations in the maze. During successive runs, many of the same cells will fire faithfully and sequentially as known landmarks are encountered. In a sense, groups of cells provide an active map of the spatial layout of the maze and of the animal's own location [21,22]. Such a dynamic navigational capability does not require more than the known electrochemical activity of the brain. Such brain mechanisms evolve in plausible ways, depending on the demands of species-specific ecological niches. Thus bats, migratory birds, dolphins, and cephalopods require sophisticated brains to navigate three-dimensional space in order to survive and reproduce. No special explanatory mechanisms needs to be invoked to explain the biology of spatial navigation across species.

In light of these consideration it is hard to understand why consciousness, richly anchored in the anatomy and physiology of the mammalian brain, should be the only biological capacity to rely exclusively on quantum principles.

8. Conclusion. Is quantum consciousness worth pursuing?

All neurons exhibit quantum-level events, but only some large-scale connectivity patterns among neurons enable consciousness, and then only in some states of the cortico-thalamic complex. This fact underscores why it is difficult to accept consciousness as the distinctive outcome of quantum interactions. It rather points to a larger-scale anatomy and physiology of conscious experiences.

The hypothesis that quantum interactions in neuronal microtubules give rise to consciousness is not supported at this time [15]. Microtubules are vital components of all plant and animal cells [6,9,16]. We know of no evidence that neuronal microtubules have different quantum properties than other cells.

It has been claimed that quantum mechanical observer effects must have some relationship to consciousness. However, we are not aware of evidence indicating that conscious brains are required to detect fundamental particles, as opposed to particle detectors or unconscious slabs of neural tissue. Particle detectors are not plausibly conscious.

Recent findings show that the microtubules of a plant, Arabidopsis thaliana, resemble neuronal microtubules. A number of microtubule-associated proteins are found in both plant cells and neurons [14]. These facts pose questions for 'quantum consciousness.' It is difficult to sketch out in detail how quantum events in some neuronal microtubules, but not others, might explain the established features of conscious contents and states.

We are beginning to learn the brain correlates of specific conscious percepts and concepts in humans and some other mammals [10,18]. Conscious brain events are commonly indexed by accurate report. The last two centuries of psychophysics have shown the striking accuracy and range of reportable conscious stimuli across the major senses, as well as 'inner senses' like visual imagery, inner speech, and the world of dreams. Non-sensory conscious events, such as abstract concepts and semantics, are also well established.

Humans with healthy brains invariably report subjective experiences for accurately reportable events. Thus the question of subjectivity is by no means excluded. It is, after all, the most prominent aspect of consciousness in our lives.

Accurate, voluntary report is still our most useful behavioral index, though new brain measures are emerging. Non-human animals can be trained to "report" conscious stimuli using a method called 'matching to sample.' That is, an animal can be trained to point to a Munsen color chip that matches the color of a sample stimulus. Animals without color receptors, like dogs and cats, cannot do this, while birds and primates can meet or exceed human performance.

It is the observable differences between conscious and unconscious brain events that allow us to study consciousness empirically. There are now thousands of such studies, and brain recording techniques continue to improve [1,4, 11,24,26].

Different oscillatory regimes in the thalamocortical system determine subjectively conscious rather than unconscious states. The anatomy of the brain does not change between sleep and waking. Rather, it is the pattern of neuronal signaling across the thalamocortical system that does.

Quantum physics may describe chemical anesthetics, neurotransmitters, or patterns of gene expression that occur as a function of the sleep–waking cycle. But to date, quantum interactions do not seem to bear robustly on the issue of consciousness 'as such.'

The biological basis of consciousness has been acknowledged as one of the fundamental unsolved questions in science [19]. The weight of evidence indicates that it is a major biological adaptation. We therefore need to understand its evolutionary, developmental, and experience-dependent foundations in the brain.

Acknowledgements

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