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Spin-mediated consciousness theory: possible roles of neural membrane nuclear spin ensembles and paramagnetic oxygen

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Summary A novel theory of consciousness is proposed in this paper. We postulate that consciousness is intrinsically connected to quantum spin since the latter is the origin of quantum effects in both Bohm and Hestenes quantum formulism and a fundamental quantum process associated with the structure of space-time. That is, spin is the "mind-pixel". The unity of mind is achieved by entanglement of the mind-pixels. Applying these ideas to the particular structures and dynamics of the brain, we theorize that human brain works as follows: through action potential modulated nuclear spin interactions and paramagnetic O_2/NO driven activations, the nuclear spins inside neural membranes and proteins form various entangled quantum states some of which survive decoherence through quantum Zeno effects or in decoherence-free subspaces and then collapse contextually via irreversible and non-computable means producing consciousness and, in turn, the collective spin dynamics associated with said collapses have effects through spin chemistry on classical neural activities thus influencing the neural networks of the brain. Our proposal calls for extension of associative encoding of neural memories to the dynamical structures of neural membranes and proteins. Thus, according our theory, the nuclear spin ensembles are the "mind-screen" with nuclear spins as its pixels, the neural membranes and proteins are the mind-screen and memory matrices, and the biologically available paramagnetic species such as O_2 and NO are pixel-activating agents. Together, they form the neural substrates of consciousness. We also present supporting evidence and make important predictions. We stress that our theory is experimentally verifiable with present technologies. Further, experimental realizations of intra-/inter-molecular nuclear spin coherence and entanglement, macroscopic entanglement of spin ensembles and NMR quantum computation, all in room temperatures, strongly suggest the possibility of a spin-mediated mind.

Introduction

Experimentally, tremendous progress has been made in neuroscience over the last several decades. Theoretically, numerous versions of quantum and non-quantum consciousness theories have been proposed over the recent years [1–8]. But, at this stage almost all these theories are speculative and none is commonly accepted. Philosophically, the age-old debate about consciousness has intensified like a raging fire [9–11]. However, despite all these efforts, what is and causes consciousness remains a deep mystery. In this paper, we propose

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a novel theory of consciousness with the hope that it would shed some light on these issues.

As further discussed below, spin is a very fundamental quantum process associated with the structure of space-time [12—14]. Indeed, modern physics leads us right down to the microscopic domain of space-time where various models of elementary particles and even space-time itself are built with spinors [15]. On the other hand, neural membranes are saturated with spin-carrying nuclei such as ^{1}H, ^{13}C and ^{31}P. Indeed, both MRI and fMRI are based on the abundance of ^{1}H in human body. Neural membranes are the matrices of brain electrical activities and play vital roles in the normal functions of a conscious brain and their major molecular components are phospholipids, proteins and cholesterols. Each phospholipid contains one ^{31}P, 1.8% ^{13}C and over 60 ^{1}H on its lipid chains. Similarly, neural membrane proteins such as ion channels and neural transmitter receptors also contain large clusters of spin-carrying nuclei. Therefore, we strongly believe that Nature has utilized quantum spin in constructing a conscious mind.

Very importantly, we believe that the mechanism of anesthetic action is closely related to the inner workings of consciousness. But how general anesthetics work is itself a 150-years old mystery [16,17]. We have already proposed within the framework of conventional neuroscience that anesthetic perturbations of oxygen pathways in both neural membranes and proteins are possibly involved in general anesthesia [17]. Each O_2 contains two unpaired valence electrons thus is strongly paramagnetic and at the same time chemically reactive as a bi-radical. It is capable of producing a large fluctuating magnetic field along its diffusing pathway thus serves as a natural contrast agent in MRI [18]. The existence of unpaired electrons in stable molecules is very rare indeed. O_2 are the only paramagnetic species to be found in large quantities in the brain besides enzyme-produced nitric oxide (NO). In addition, O_2 is an essential component for energy production in the central nervous system.

Both O_2 and NO, the latter being a unstable free-radical with one unpaired electron and a recently discovered small neural transmitter, are well known in spin chemistry — a field focused on the study of free-radical mediated chemical reactions where very small magnetic energies can change non-equilibrium spin conversion process [19,20]. Thus O_2 and NO may serve as spin-catalysts in consciousness-related neural biochemical reactions such as those dual path reactions initiated/driven by free-radicals [21].

Nature of spin

Unlike mass and charge that enter a dynamic equation as arbitrary parameters, spin reveals itself through the structure of the relativistic quantum equation for fermions such as electrons [12]. Penrose [13,14] had considered early on that spin might be more fundamental than space-time and invented spinor and twistor algebras for a combinatorial description of space-time geometry. Bohm and Hiley [22] generalized the twistor idea to Clifford algebra as a possible basis for describing Bohm's implicit order. Recently various spin foams have been formulated as extensions to Penrose's spin networks for the purpose of constructing a consistent theory of quantum gravity [23,24].

In Hestenes' geometric picture [25], the zitterbewegung associated with the spin of the Dirac electron is qualitatively shown to be responsible for all known quantum effects of said electron and the imagery number i in the Dirac equation is said to be due to electronic spin. Second, in Bohmian mechanics the quantum potential is responsible for quantum effects [26]. Salesi and Recami [27] has recently shown that said potential is a pure consequence of internal motion" associated with spin evidencing that the quantum behavior is a direct consequence of the fundamental existence of spin. Esposito [28] has expanded this result by showing that "internal motion" is due to the spin of the particle, whatever its value. Very recently, Bogan [29] has further expanded these results by deriving a spin-dependent gauge transformation between the Hamilton—Jacobi equation of classical mechanics and the time-dependent Shrödinger equation of quantum mechanics that is a function of the quantum potential in Bohmian mechanics. Third, Kiehn [30] has shown that the absolute square of the wave function could be interpreted as the vorticity distribution of a viscous compressible fluid that also indicates that spin is the process driving quantum effects.

Many others have also study the nature of spin from both classical and quantum-mechanical perspectives [31—33]. For example, Newman showed that spin might have a classical geometric origin. Galiautdinov [32] has considered a theory of space-time quanta and suggested that spin might manifest the atomic structure of space-time. Finkelstein [33] is proposing that spin derives from a swap — a projective permutation operator, and the two-valued spin representation from a deeper two-valued statistics. Sidharth [34,35] has shown that spin is symptomatic of the non-commutative geometry of space-time at the Compton scale of a fermion and the three dimensionality of the space result from the spinorial behavior of fermions. He further showed that mathematically an imaginary shift of the space-time coordinate in the Compton scale of a fermion introduces spin 1/2 into general relativity and curvature to the fermion theory [34,35]. The reason why an imaginary shift is associated with spin is to be found in the quantum-mechanical zitterbewegung within the Compton scale and the consequent quantized fractal space-time [34,35]. Further, according to Sidharth [34,35], a fermion is like a Kerr—Newman Black Hole within the Compton scale of which causality and locality fails.

Mystery of general anesthesia

There is no commonly accepted theory on how general anesthetics work [16,17]. However, there are two schools of thoughts on the issue. The first and oldest is the "lipid theory" which proposes that anesthetics dissolve into cell membranes and produce common structural perturbation resulting in depressed function of ion channels and receptors that are involved in brain functions [16]. The second, more popular and recent theory is the "protein theory" which suggests that anesthetics directly interact with membrane proteins such as ion channels and receptors that are involved in brain functions. But the protein theory does not seem to square well with the low affinity and diversity of the general anesthetics. There is no direct experimental evidence to support either theory [17].

However, both theoretical and experimental studies have shown that many general anesthetics cause changes in membrane structures and properties at or just above the clinical concentrations required for anesthesia [16,36,37]. Since both O_2 and general anesthetics are hydrophobic, we have proposed within the framework of conventional neuroscience that general anesthetic may cause unconsciousness by perturbing O_2 pathway in neural membranes and O_2-utilizing proteins, such that the availability of O_2 to its sites of utilization is reduced, which in turn triggers cascading cellular responses through O_2-sensing mechanisms, resulting in general anesthesia [17].

We have also been asking the question whether anesthetic perturbations of neural membranes and oxygen pathways themselves are the direct cause of unconsciousness. This conjuncture requires that O_2 and neural membranes be directly involved in consciousness. Indeed, The low affinity, diversity and pervasiveness of general anesthetics point us to this direction. If we assume that consciousness is an emergent property of the brain [9] and further liken consciousness to the formation of ice at 0 °C, the anesthetic action would be like the action of salt which prevents ice formation.

Nature of consciousness

There is no coherent view as to what is and causes consciousness. Some neuroscientists would say that it is the connections between the neurons and the coherent firing patterns thereof [2,6]. Some physicists would propose that it is connected to the measurement problem in quantum theory and thus the solution lies there [1,3,5,7]. A few philosophers would suggest that it is an emergent property of the complex brain [9] or new kinds of properties and laws are required [11]. For sure such disarray has its historical reasons. Ever since Descartes promoted his dualism philosophy in the 17th century, science has been for the most part steered clear from this subject until very recently.

Philosophically, Searle [9] argues that consciousness is an emergent biological phenomenon thus cannot be reduced to physical states in the brain. Chalmers [11] argues that consciousness cannot be explained through reduction, because mind does not belong to the realm of matter. In order to develop a consciousness theory based on this approach, Chalmers [11] suggests expanding science in a way still compatible with today's scientific knowledge and outlines a set of fundamental and irreducible properties to be added to space-time, mass, charge, spin etc. and a set of laws to be added to the laws of Nature. Further, he considers that information is the key to link consciousness and the physical world.

On the theoretical front, there are quite a few quantum theories of mind [1,3—5,7,8]. Among these, Penrose's Objective Reduction ("OR") together with Hameroff's microtubule computation is perhaps the most popular, and the combination of the two produced the Orchestrated Objective Reduction ("Orch OR") in microtubules [1,7,8]. According to Penrose [1,7], each quantum state has its own space-time geometry, thus superposition of quantum states entails superposition of different space-time geometries. Under certain conditions, such space-time geometric superposition would separate under its own "weight" through a non-computable process, which in turn would collapse said quantum state superposition [1,7]. Hameroff and Penrose [8] suggested that such self-organized OR could occur in microtubules because of their particular structures, thus, born the Orch OR. According Orch OR, each collapse of macroscopic space-time geometry superposition corresponds to a discrete conscious event [8]. In addition, it seems that Penrose [1,7] accepts a separate mental world with grounding in the physical world.

There are also a number of theories based on conventional neuroscience [2,6]. Our view on these is that whatever the final accepted version based on neuroscience ("classical physics"), it could be accepted as classically correct. The reason is that we must rely on the classical parts of the brain working according to conventional neuroscience to provide us the necessary neural components and wirings such as coherent neural firings, neurotransmitter releases and neural plasticity to support any realistic quantum activities of the brain. The situation is much like that in quantum computation where classical components form the supporting system of a quantum computer. Without these classical components, quantum computation could not be implemented at all.

In comparison, our working philosophy is that consciousness is grounded at the bottom of physical reality and emerges from the collective dynamics of known physical candidates inside the brain. Next we ask "where" and "how". To answer these, we take the reductionist approach both down to the end of physics to see what is left there and to the microscopic domain of a neuron to see what may be really important for the functioning of a conscious brain. What we found is that there is almost nothing left at the end of physics except the fundamental ideas of quantized space-time and spin. On the other hand, we found that what may be really important in the microscopic domain of a neuron are the nuclear spin ensembles and the fluxes of biologically available unpaired electrons carried by small molecules such as O_2 and NO. Naturally, we draw the conclusion that quantum spin together with its connection to space-time geometry is needed to ground consciousness in physical reality such that conscious experience emerges from the successive collapses of various entangled neural nuclear spin-states.

Specifically, we try to answer these questions: (1) what are the neural substrates of consciousness; (2) what physical processes are involved in conscious experience; (3) what physical and biochemical process are involved in connecting consciousness to the classical neural networks of the brain; (4) what binding mechanism allows the mind to achieve unity.

General postulates

With above discussions in mind, we present the following Postulates: (a) consciousness is intrinsically connected to quantum spin; (b) the mind-pixels of the brain are comprised of the nuclear spins distributed in the neural membranes and proteins, the pixel-activating agents are comprised of biologically available paramagnetic species such as O_2 and NO, and the neural memories are comprised of all possible entangled quantum states of the mind-pixels; (c) action potential modulations of nuclear spin interactions input information to the mind-pixels and spin chemistry is the output circuit to classical neural activities; (d) consciousness emerges from the collapses of those entangled quantum states which are able to survive decoherence, said collapses are contextual, irreversible and non-computable and the unity of consciousness is achieved through quantum entanglement of the mind-pixels.

In Postulate (a), the relationship between quantum spin and consciousness are defined based on the fact that spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism [25,27–29] and a fundamental quantum process associated with the structure of space-time [12–14]. Combining this fundamental idea with those stated in Postulates (b)–(d) allows us to build a qualitatively detailed working model of consciousness as discussed later.

In Postulate (b), we specify that the nuclear spins in both neural membranes and neural proteins serve as the mind-pixels and propose that biologically available paramagnetic species such as O_2 and NO are the mind-pixel-activating agents. We also propose that neural memories are comprised of all possible entangled quantum states of mind-pixels. This concept of memory is an extension to the associative memory in neuroscience as will be discussed later.

In Postulate (c), we propose the input and output circuits for the mind-pixels. As shown in a separate paper, the strengths and anisotropies of nuclear spin interactions through *J*-couplings and dipolar couplings are modulated by action potentials. Thus, the neural spike trains can directly input information into the mind-pixels made of neural membrane nuclear spins. Further, spin chemistry can serve as the bridge to the classical neural activities since biochemical reactions mediated by free-radicals are very sensitive to small changes of magnetic energies as mentioned earlier and further discussed later [19—21].

In Postulate (d), we propose how conscious experience emerges. Since there are several interpretations of the measurement problem in quantum mechanics, we choose to accept the collapsing view [1,7]. Thus, we adopt a quantum state collapsing scheme from which conscious experience emerges as a set of collapses of the decoherence-resistant entangled quantum states. We further theorize that the unity of consciousness is achieved through quantum entanglements of these mind-pixels [5].

Illustrations of spin-mediated consciousness

Overview

Fig. 1 is a highly schematic drawing of the overall picture of a spin-mediated consciousness model proposed herein. At the top of Fig. 1, a two-neuron network is shown. The connections are self-explanatory. The neural activities of the postsynaptic membrane are immediately shown below the neurons in Fig. 1. These activities include biochemical reactions immediately following the release of neurotransmitters into the synaptic cleft, the ensuing collective activities of multiple ion channels and the action potentials and their propagations thereof, and other enzymatic activities.

The present model is mainly concerned with the dynamics of the nuclear spin ensembles in neural membranes and proteins such as those on the dendrites and soma under modulations by action potentials and activations by paramagnetic species such as rapidly tumbling and diffusing O_2 and neural transmitter NO, and the connections of such dynamics to conscious experience. The input and output interface of the neural nuclear spin ensembles are schematically shown in the middle of Fig. 1. On the bottom of Fig. 1, what the conscious brain perceives is schematically shown. The neural substrates and mechanism of the spin-mediated consciousness are described below.

Nuclear spin ensembles

Fig. 2 shows side-by-side a typical phospholipid found in neural membranes together with the diffusing O_2. A similar but much complex picture can be drawn for a neural protein. As can be seen, each phospholipid molecule contains one ^{31}P, less than one ^{13}C (1.1%) and more than 60 ^{1}H on its two lipid chains. Because the small mobility of nuclei and weak interactions of nuclear spins with their environments, nuclear spins have long relaxation time after excitations [18]. This property of nuclear spins is ideal for them to serve as the mind-pixels. Importantly, these nuclear spins can form various intra-/inter-molecularly entangled quantum states under different external activations through *J*-couplings and dipolar couplings [38—40].

Activation agents

The unpaired electrons attached to the paramagnetic species such as O_2 and NO can interact with nuclear spins through their large magnetic dipoles and collision-induced Fermi-contact mechanism [41] thus activating the neural nuclear spin ensembles. Indeed, because the magnetic dipole moment of an unpaired electron is 658 times larger than that of the ^{1}H nucleus, O_2 and NO can, respectively, produce magnetic fields 1316 and 658 times larger than ^{1}H [41]. In addition, O_2 and NO are hydrophobic small molecules so their concentrations in neural membranes are much higher than in aqueous solutions such as cytoplasma [42]. Thus, as they rapidly tumble and diffuse, they produce microscopically strong and fluctuating magnetic fields. O_2 are the predominant sources of internal magnetic fields in neural membranes as evidenced by the strong effect of O_2 on spin—spin and spin—lattice relaxation rates [42,43].

Spin-mediated mechanism

The mechanism of spin-mediated consciousness is concisely stated here and the related issues such as decoherence effect are treated in next subsection. Through action potential modulated nuclear spin interactions and paramagnetic O_2/NO driven activations the nuclear spins inside neural membranes and proteins form various entangled spin states some of which survive rapid decoherence through quantum Zeno effects or in decoherence-free subspaces and then collapse contextually through non-computable and irreversible means thus producing consciousness and, in turn, the collective spin dynamics associated with said collapses have effects through spin chemistry on classical neural activities thus influencing the classical neural networks of the brain. Our proposal calls for extension of associative encoding of neural memories to the

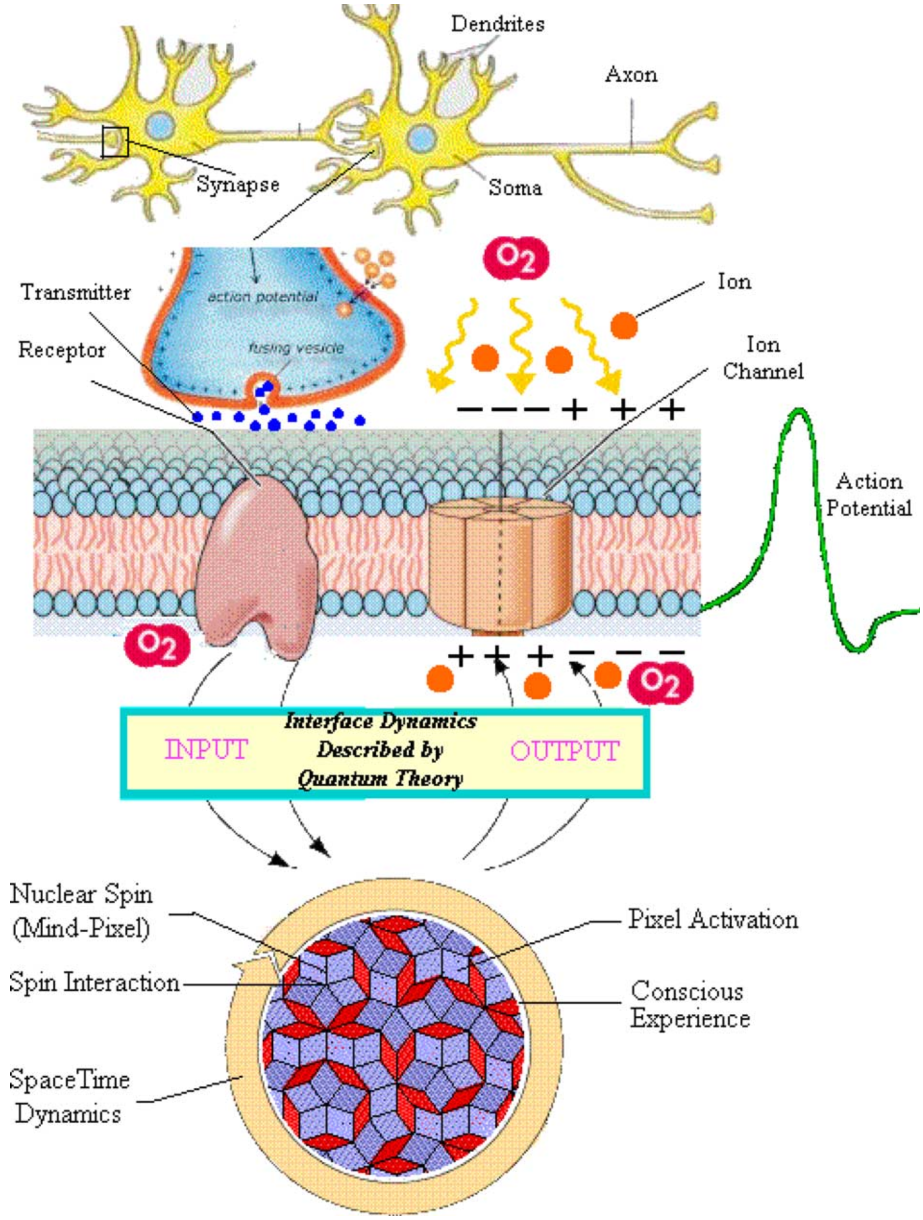

Figure 1 Illustration of spin-mediated consciousness theory. The drawing is self-explanatory except the part dealing with conscious experience. See text for detailed explanations.

dynamical structures of neural membranes and proteins.

Therefore, according to the present theory: (a) the dynamical nuclear spin ensembles are the "mind-screen" with nuclear spins as its pixels; (b) the neural membranes and proteins are the mind-screen and memory matrices; (c) the fluxes of biologically available paramagnetic O_2/NO are the beam for pixel-activations. Together, they form the neural substrates of consciousness. An analogy to this is the mechanism of liquid crystal display (LCD) where information-carrying electric voltages applied to the pixel cells change the optical properties of the constituent molecules such that when lights pass through these cells their phases get rotated differently which in turn represent different information to the viewer of the LCD screen [44].

Quantum coherence and decoherence

The decoherence effect which causes a quantum system to lose quantum coherence through interactions with its environment is a major concern for any quantum theory of the brain and is hotly debated [45,46]. However, nuclear spins only have

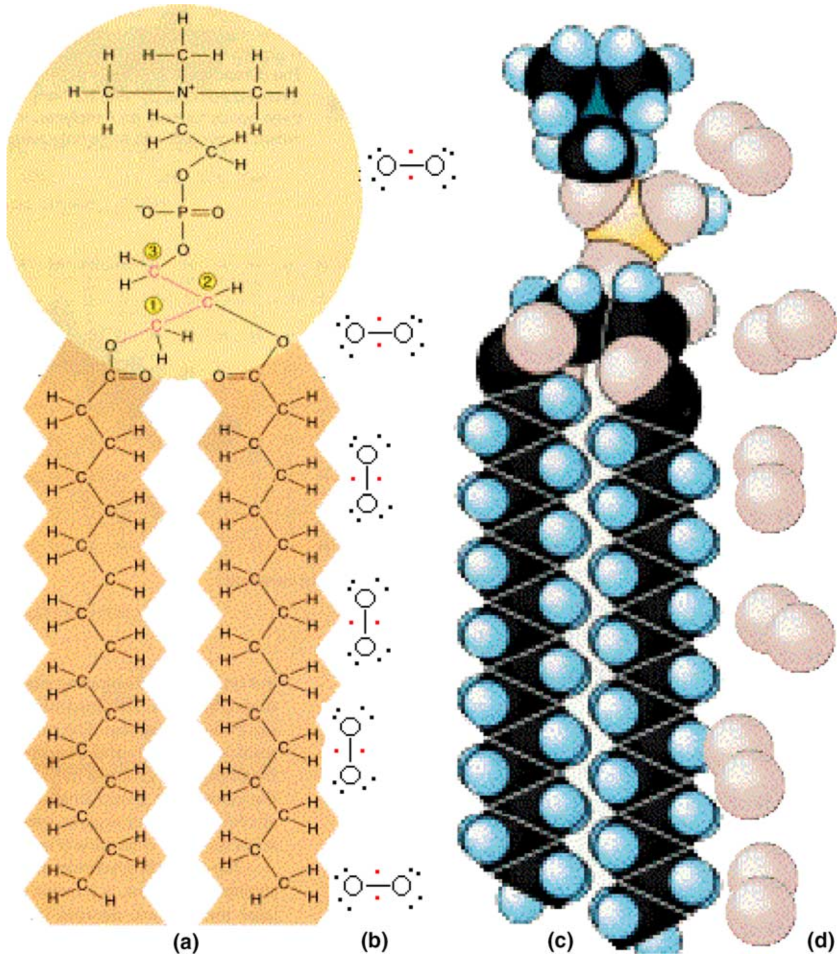

Figure 2 Schematic drawings of chemical structure (a) and atomic model (c) of a typical phospholipid with diffusing O_2 in Lewis structure (b) and atomic model (d) shown along the side. Two unpaired electrons of O_2 are shown in Lewis structure as two red dots (b). In the atomic model, the white, black, purple and orange balls, respectively, represent hydrogen, carbon, oxygen and phosphonium atoms. ^{1}H, ^{13}C and ^{31}P are spin-carrying nuclei.

weak interactions with their environments thus long relaxation time after excitation [18]. Indeed, there are both theoretical and experimental studies [38—40,47—50] indicating the possibility of large-scale quantum coherence with entanglement in the nuclear spin ensembles distributed in the neural membranes and proteins. Paradoxically, the interactions of the neural membrane nuclear spin ensembles with their noisy brain environments may even enhance quantum coherence through quantum Zeno effect which prevents a quantum system to evolve/decohere through repeated collisions with their environments [5]. Further, studies show that decoherence-free subspaces can exist within the Hilbert space of a complex quantum system [51].

In a series of experiments, Khitrin et al. [38—40] have demonstrated that a cluster of dipolar coupled ^{1}H nuclear spins in the molecules of a nematic liquid crystal at room temperature can be manipulated to achieve long-lived intra-molecular quantum coherence with entanglement such that a large amount of information may be stored in said cluster. In particular, they have succeeded in storing at room temperature a 2D pattern consisting of 1025 bits of information in the proton nuclear spin-states of a molecular system of said nematic liquid crystal and then retrieved the same as a stack of NMR spectra [38—40].

Second, about a decade ago Warren et al. [47,48] discovered long-range inter-molecular multiple-quantum coherence in NMR spectroscopy and imaging and have since successfully applied said coherence as MRI contrast agents. Indeed, they found that even the inter-molecular dipolar couplings of the nuclear spins at distances larger than 10 μm are not averaged away by diffusions [47,48].

Third, Julsgaard et al. [49] have first theoretically predicted and then experimentally demonstrated at room temperature a long-lived entanglement of two macroscopic spin ensembles formed by two caesium gas samples each of which contains about 10^{12} atoms. The entangled spin-state can be maintained for 0.5 ms and was generated via interactions of the samples with a pulse of light [49]. The state they demonstrated is not a maximally entangled "Schrödinger cat" state but a state similar to a two-mode squeezed state; thus, it is an example of a non-maximally entangled state [49]. In addition, Kun et al. [50] have theoretically predicted a "Schrödinger cat" state to be found in highly excited and strongly interacting many-body system.

These results apparently contradict the claim that there is no large-scale quantum coherence in the noisy brain [45]. At least, this claim does not seem to apply to the nuclear spin ensembles in neural membranes and proteins. Further, in the case of Penrose—Hameroff [8] microtubule model, it was strongly argued by Hagan et al. [46] that Tegmark's theoretical calculations also do not apply there. Indeed, even if we assume this claim is true, consciousness can still emerge from the statistical mixtures of coherent and incoherent quantum states of the mind-pixels, as long as we either accept some kind of emergence theory [9] or take a dualistic approach [4,11] as will be discussed again later.

We adopt Penrose's [1,7] long-standing view that human thought may involve non-computable processes, as Gödel's theorem of incompleteness would suggest. According to Gödel, any consistent system of axioms beyond a certain basic level of complexity yields statements that cannot be proved or disproved with said axioms. Yet human can decide whether those statements are true, thus human thought cannot be reduced to a set of rules or computations [1,7]. So where can one find non-computable process in physics? Obviously it cannot be found in classical physics because classical physics is deterministic so, in principle, can be simulated by a computer [1,7]. Thus, Penrose [1,7] reasoned that some kind of non-computable quantum process must be involved in consciousness and further suggested gravity-induced reduction ("R") process of quantum state superposition to be the candidate. One may recall that, according to Einstein's theory of general relativity, gravity is space-time geometry and, further, as we have discussed before quantum-mechanical spin is associated with the structure of space-time. Therefore, the quantum state of spin must be connected to the underlying space-time geometry. However, we still have the task of working out the details in future research. This will be especially difficult because at the present we do not have a satisfactory theory of quantum gravity.

Consciousness explained

The explanation of consciousness in accordance with our spin-mediated theory is schematically shown at the bottom of Fig. 1. The geometry inside the spinning circle represents conscious experience and is part of a Penrose tiling [1]. It symbolizes that consciousness emerges from the non-computable collapses of entangled quantum states of the mind-pixels under the influence of space-time dynamics schematically shown as the spinning circle. The edges in the Penrose tiling represent the nuclear spins in neural membranes and proteins as mind-pixels, the nodes represent interactions between these nuclear spins through *J*-couplings and dipolar couplings and the colors represent activations of mind-pixels by biologically available paramagnetic species such as O_2 and NO. The whole tiling pattern in Fig. 1 represents conscious experience and the underlying space-time geometry. This pattern successively evolves under repeated activations by the paramagnetic species representing successive collapses of the entangled quantum states of the mind-pixels that have survived decoherence as a stream of conscious experience.

Alternative approaches to consciousness

If we assume that there is no large-scale quantum coherence in the noisy brain because of decoherence [45], how can consciousness still emerge from the statistically mixed quantum states of the nuclear spin ensembles in neural membranes and proteins? There are indeed at least two ways out. The first is to adopt an emergence theory [9] and the second is to take a dualistic approach [4,11]. Here, we will focus our discussion on the dualistic approach.

In such approach we can propose that mind has its own independent existence and reside in a pre-space-time domain. Then, the question becomes how does mind process and harness the information from the brain so that it can have conscious experience? We can theorize that conscious experience emerges from those quantum states of the mind-pixels in the statistical mixtures that have grabbed the attention of the mind through quantum Zeno effect [5] or some non-local means in pre-space-time. Indeed, the many-mind interpretation of quantum theory as proposed by Donald [3] supports this type of formulation. Thus, in this scenario, mind does not depend on large quantum coherence to work.

Furthermore, each nuclear spin is a quantum bit, each O_2 spin triplet is tightly entangled two-qubit and there exist coherent and incoherent intramolecular superpositions of multiple nuclear spins under external stimulations [38—40]. So, it is plausible that mind could utilize quantum statistical computations similar to those proposed by Castagnoli and Finkelstein [52]. In their model, a triode network made of triplet pairs of spin 1/2 fermions and their quantum statistical relations due to particle indistinguishability was utilized to implement the computation, together with a randomly varying magnetic field as heat bath for annealing [52]. The scheme develops quantum parallelism through the incoherent superposition of parallel computation paths (i.e., the mixtures). It replaces the superposition of coherent parallel computation paths with the almost indestructible superposition of different permutations of identical particles subject to a given statistics thus surviving decoherence [52].

Associative memory model

We have proposed that neural memories are comprised of all possible entangled quantum states of the nuclear spins inside neural membranes and proteins. This proposal calls for extension of the existing associative memory concept in neuroscience to include all possible conformations of neural membranes and proteins in a single neuron [53]. A few illustrations are given here. Fig. 3(a) schematically shows a patch of neural membrane containing only the same phospholipids. Such a membrane is much like a blank tape. Fig. 3(b) shows the same neural membrane after cholesterols are added. The changes in membrane configuration are quite noticeable [54,55]. These changes can represent memory or information. Fig. 3(c) shows the chemical structure and atomic model of a stearic acid molecule — a saturated fatty acid. Fig. 3(d) shows the chemical structure and atomic model of oleic acid molecule — an unsaturated fatty acid. The only difference between the two fatty acids is that the latter contains a double bond in the middle that causes its kink formation when the double bond is the *cis* form. When the double bond is in the *trans* form, the chain is doubly bent so there is no kink. Certainly insert either one of the fatty acids into the membrane shown in Fig. 3(b) would further increase its complexity thus information content. Furthermore, insertions of proteins to neural membranes also significantly change their conformation and dynamics surrounding the inserted proteins [56]. Thus, inserting different proteins to neural membranes both in numbers and types can significantly increase the information content of the neural membranes.

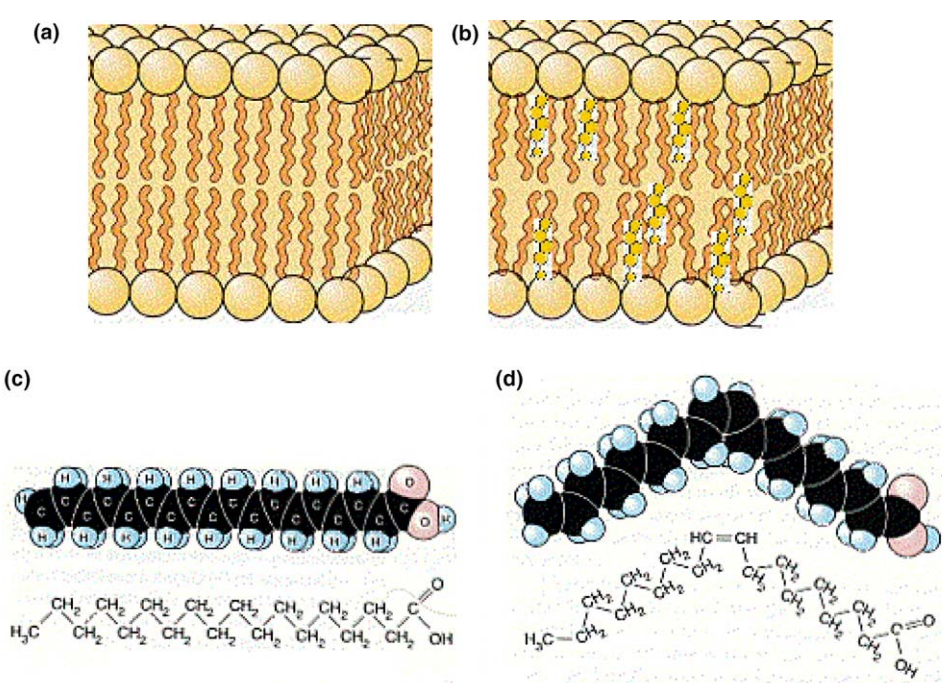

Figure 3 Illustration of neural memory: (a) shows a neural membrane containing only the same phospholipids; (b) shows the neural membrane after cholesterols are added; (c) shows the chemical structure and atomic model of a stearic acid molecule; (d) shows the chemical structure and atomic model of oleic acid molecule.

Input and output circuits

We have suggested that action potential modulations of nuclear spin interactions input information to the mind-pixels and spin chemistry is the output circuit to classical neural activities. With respect to the input circuit, published studies show that the dynamics of membrane proteins significantly affect the dynamics of surrounding membranes [53,56]. Secondly, due to the very small thickness of the neural membrane (~10 nm), even the small voltage (~50 mV) of an action potential can create enormous oscillating electric field inside the neural membranes that in turn can affect the conformations and dynamics of the membrane components such as phospholipid and proteins [57,58]. Indeed, the strengths and anisotropies of nuclear spin interactions through *J*-couplings and dipolar couplings are modulated by action potentials as will be shown in a separate paper. Thus, the neural spike trains can directly input information into the mind-pixels made of neural membrane nuclear spins.

Secondly, the weak magnetic field produced collectively by all neural activities may also directly serve as the input. However, the magnitude of said magnetic field is only in the order of 10^{-12} T [59]. In comparison, O_2 and NO can produce a fluctuating local magnetic field as high as a few Tesla according to our own calculations. Thus, the effect of said weak magnetic field on the dynamics of mind-pixels is probably small unless non-linear processes such as stochastic resonance are involved.

Further, we have already pointed out earlier that spin chemistry can serve as the output circuit to classical neural activities because biochemical reactions mediated by free-radicals are very sensitive to small changes of magnetic energies as discussed previously. Indeed, many biochemical reactions mediated by radical pairs and biradicals, such as those dual path radical reactions driven/initiated by NO and active oxygen species, have been found to be influenced by the magnetic field in their local environment [19,20]. Thus, the functional output of the mind-pixels, being the varying local magnetic field generated by the dynamics of the nuclear spin ensembles as mind-pixels, can directly affect classical neural activities. Further, there may be other mechanisms through which the mind-pixels can influence the classical neural activities of the brain.

Mechanism of anesthetic action

As mentioned earlier in this paper, the mechanism of anesthetic action is closely related to the inner workings of consciousness [17]. We describe here said mechanism in accordance with our spin-mediated theory. Fig. 4(a) schematically shows the normal diffusion of O_2 and NO without anesthetics dissolved into the neural membranes and proteins. As these molecules rapidly diffuse through the membranes, they collide with the neural membrane components and generate strong and fluctuating internal magnetic fields thus activating the nuclear spin ensembles inside these membranes. Fig. 4(b) schematically shows anesthetic perturbations of O_2 and NO pathways and neural membranes themselves by anesthetic molecules and the resulting distortion and/or obstruction of these pathways. Such perturbations render O_2 and NO not able to perform their normal activation functions thus resulting in unconsciousness.

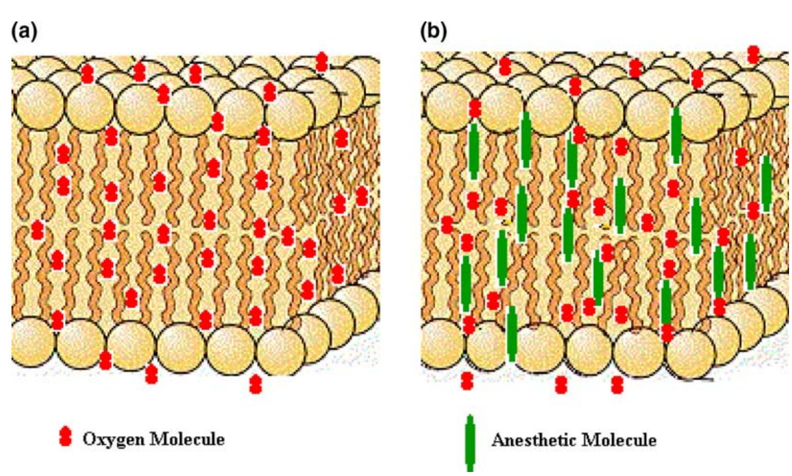

Figure 4 Illustration of anesthetic action: (a) shows the normal diffusion of O_2 without anesthetics dissolved into neural membranes; (b) shows anesthetic perturbations of O_2 pathways and neural membranes themselves.

Predictions and supporting evidence

Several experimentally verifiable predictions can be drawn from our spin-mediated consciousness theory: (1) significant replacement of ^1H with ^2H will affect or disrupt consciousness; (2) significant external disturbances to the dynamics of the nuclear spin ensembles in neural membranes and proteins will interfere with normal conscious functions; (3) significant drug-induced disturbances to the structure and dynamics of the neural membranes and protein themselves will affect or disrupt consciousness; (4) significant drug-induced disturbances to the O_2 pathways inside the neural membranes will diminish or block consciousness; (5) significant lack of O_2 in neural membranes will directly affect or disrupt consciousness even if everything else in the brain functions normally. Of course, other predictions and inferences can also be drawn from the present theory. But we will focus our discussions on the above listed a few to see whether there are any experimental evidence supporting these predictions.

With respect to prediction (1), there are published results concerning the biological effects of heavy water (^2H_2O or D_2O) that lend indirect support to our proposals [60]. Indeed, the only observable physical and chemical difference between regular and heavy water is that the latter has a slightly higher viscosity [60]. It was reported that rats restricted to heavy water (99.8%) would drink it freely the first day, then drank progressively less and died within 14 days [61]. It was also reported that the incremental increase of the amount of heavy water in regular drinking water lengthened the 24-h clock of the Circadian rhythm in blind hamsters or normal hamsters kept in constant darkness [62]. In principle, these observations can be explained as animals literally loosing their minds because of the loss of their mind-pixels due to gradual ^2H substitutions of ^1H in neural membranes and proteins. The complication is that the higher viscosity of heavy water might have also contributed to the observed effects. It is possible to design an experimental procedure to either account for or exclude those effects attributable to the higher viscosity.

With respect to prediction (2), there are also quite a few published studies based on transcranial magnetic stimulation ("TMS") that can be at least partially explained based on our theory [63,64], although common wisdom is that TMS induces electrical currents in the brain, causing depolarization of cellular membranes and thereby neural activation [63]. It has been found that depending on the locations of stimulation TMS affects the test subject's verbal ability, visualization and other conscious functions [64]. According to our theory, TMS can directly affect the dynamics of nuclear spin ensembles in neural membranes and proteins which in turn result in altered, diminished and/or disrupted conscious functions of the brain.

With respect to predictions (3) and (4), many general anesthetics have been found to disturb the structures and dynamics of neural membranes [16,36,37]. Thus, the mechanism of their action can be interpreted, according our spin-mediated theory, as caused by their direct effects on O_2 pathways and nuclear spin ensembles inside the neural membranes and proteins. Our other paper contains a detailed treatment on anesthetic perturbations of oxygen pathways and membranes themselves [17]. Here we will focus on one particularly small anesthetic agent, the nitrous oxide (N_2O), also known as the laughing gas. Indeed, the size of N_2O is similar to that of O_2 but it does not contain unpaired electrons and is not reactive. It has low polarity that makes it soluble in both water and lipid. Thus, it can be carried to the brain through blood stream and accumulate in the neural membranes. Inhalation of N_2O will cause disorientation, euphoria, numbness and ultimately loss of consciousness if the inhalation dosage is high. The cellular mechanism of these actions by N_2O is so far unknown but seems confined to postsynaptic targets [65]. On the other hand, its closely related "cousin" NO contains one unpaired electron and has been discovered as the first small and highly diffusive neural transmitter produced in the brain through enzymatic reactions [66]. According to our theory, there indeed exist a natural and straightforward explanation. By dissolving into neural membranes in an inhalation-dose-dependent fashion, N_2O gradually displace O_2 in the neural membranes thus diminish or disrupt the activating function of O_2.

With respect to prediction (5), it is probably very hard to deprive brain O_2 and yet at the same time require its neurons to keep their metabolic functions normal since O_2 is an essential component of brain energy production. However, according to our theory in the case of temporary-hypoxia-induced unconsciousness such as that due to sudden loss of air pressure on an airplane, the actually cause may not be the depletion of brain energy resources because of the lack of O_2 but the direct loss of O_2 as the activating agents.

Finally, we briefly turn our attention to the associative memory model proposed herein. There are tens of thousands of research papers on the subject of synaptic plasticity/modification [67]. The commonly accepted assumption in neuroscience is that synaptic efficacy is both necessary and sufficient to account for learning and memory [53]. Our associative memory model does not conflict with the synaptic efficacy view but extend it to the sub-neural and microscopic domain. Studies show that neural activities modify not only the synaptic efficacy but also the intrinsic properties of the neuron [53].

Discussions and conclusions

Our working philosophy in this paper has been that consciousness is grounded at the bottom of physical reality and emerges from the collective dynamics of known physical candidates inside the brain. We strongly believe that quantum spins are such candidates because they are one of the most fundamental entities in modern physics and, on the other hand, neural membranes and proteins are saturated with spin-carrying nuclei. We have applied reductionist approaches in both physics and neuroscience to reach our tentative conclusions. However, our theory as it stands now is speculative and only qualitatively detailed. We are building a quantitative model and the results will be reported in the near future. We have made important predictions from our theory and presented experimental evidence in support of the same. We have also suggested new experiments to verify the present proposals. Indeed, recent experimental realizations of intra-/inter-molecular nuclear spin coherence and entanglement, macroscopic entanglement of spin ensembles and NMR quantum computation, all in room temperatures, strongly suggest the possibility of a spin-mediated mind.

At this point, one crucial question the reader may ask is how can we explain that cognitive functions seem in general insensitive to environmental and even medical strength external magnetic fields such as those used in MRI? First, the strengths of environmental magnetic fields are in the range of 10^{-4}—10^{-6} T [68]. In comparison, the internal fluctuating magnetic fields can be as high as several Tesla as we have estimated in a separate paper. Thus, the internal magnetic fields overshadow the environmental ones. But the strengths of magnetic fields used in MRI are in the range of 0.064—8.0 T [69] that is comparable to or even higher than the strengths of the internal magnetic fields. So additional explanations are called for. Indeed, the net magnetization of nuclear spins even by magnetic field of several Tesla is only about a few ppm at room temperature [70] which shows that even strong static magnetic fields only have small effects on the thermal dynamics of the neural nuclear spin ensembles. Third, to the extent that said spin ensembles are disturbed by external magnetic fields, it is argued that most of these disturbances do not represent meaningful information to the brain and, further, the brain likely have developed other mechanisms through evolution to counter the effects of most external disturbances. In the cases where external magnetic disturbances were reported to have observable cognitive effects, the above suggestion provides a possible basis for interpreting these effects as the results of said disturbances either too large or containing meaningful information to the brain.

However, we would like to caution that even if our theory is confirmed partly or as a whole by more experiments it will only mark the beginning of a new direction towards a better understanding of consciousness. There are so many questions need to be answered, especially those "hard problems" [11]. For example, what are the roles of the nuclear spins carried by different nuclei such as ^{1}H, ^{13}C and ^{31}P? Do they represent different emotions or feeling of our mind? What are the roles of different biologically available paramagnetic species such as O_2 and neural transmitter NO? Do they activate different perceptions of mind?

In conclusion, we have proposed a novel theory of consciousness in which quantum spins play the central role as mind-pixels and the unity of mind is achieved by entanglement of these mind-pixels. To justify such a choice, we have shown that spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism and a fundamental quantum process associated with the structure of space-time. Applying these ideas to the particular structures and dynamics of the brain, we have theorized how consciousness emerges from the collapse of the decoherence-resistant entangled spin-states via contextual, non-computable and irreversible processes. We have suggested that these entangled spin-states are formed through action potential modulated nuclear spin interactions and paramagnetic O_2/NO driven activations and survive rapid decoherence through quantum Zeno effects or in decoherence-free subspaces. We have further suggested that the collective spin dynamics associated with said collapses have effects through spin chemistry on classical neural activities thus influencing the neural networks of the brain. Our proposals imply the extension of associative encoding of neural memories to the dynamical structures of neural membranes and proteins. Therefore, according our theory the neural substrates of consciousness are comprised of the following: (a) nuclear spin ensembles embedded in neural membranes and proteins which serve as the "mind-screen" with nuclear spins as the pixels; (b) the neural membranes and proteins themselves which serve as the matrices for the mind-screen and neural memories; (c) the biologically available paramagnetic species such as O_2 and NO which serve as the pixel-activating agents.

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