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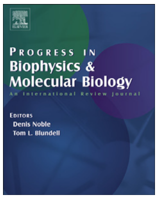

Quantum information theoretic approach to the mind–brain problem

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ABSTRACT

The brain is composed of electrically excitable neuronal networks regulated by the activity of voltage-gated ion channels. Further portraying the molecular composition of the brain, however, will not reveal anything remotely reminiscent of a feeling, a sensation or a conscious experience. In classical physics, addressing the mind–brain problem is a formidable task because no physical mechanism is able to explain how the brain generates the unobservable, inner psychological world of conscious experiences and how in turn those conscious experiences steer the underlying brain processes toward desired behavior. Yet, this setback does not establish that consciousness is non-physical. Modern quantum physics affirms the interplay between two types of physical entities in Hilbert space: unobservable quantum states, which are vectors describing what exists in the physical world, and quantum observables, which are operators describing what can be observed in quantum measurements. Quantum no-go theorems further provide a framework for studying quantum brain dynamics, which has to be governed by a physically admissible Hamiltonian. Comprising consciousness of unobservable quantum information integrated in quantum brain states explains the origin of the inner privacy of conscious experiences and revisits the dynamic timescale of conscious processes to picosecond conformational transitions of neural biomolecules. The observable brain is then an objective construction created from classical bits of information, which are bound by Holevo's theorem, and obtained through the measurement of quantum brain observables. Thus, quantum information theory clarifies the distinction between the unobservable mind and the observable brain, and supports a solid physical foundation for consciousness research.

1. Introduction

The essence of consciousness is *experience* (Nagel, 1974, 1987, 2012). Through conscious experiences such as the perceived colors of the rainbow, the pleasant sound of a musical instrument, the fresh smell of the sea breeze, or the wet touch of the water, we access the surrounding physical world and become aware of our own bodies (Georgiev, 2017). The introspective access to our conscious experiences is privately reserved only for us from a subjective, phenomenal, first-person perspective, and it is denied to others who happen to observe us from an objective, third-person perspective (Nagel, 1974, 1987, 2012). It is an empirical fact that the very process of observation of someone else's brain does not elicit in us experiences that are identical with those experienced by the observed brain (Georgiev, 2020). Consequently, we do not have at our disposal an objective method to determine whether any other living or non-living physical system is conscious or not. The unobservability of conscious experiences does not prevents us from being able to specify the particular subject whose experiences we are talking about, or to characterize the physical circumstances under which certain conscious experiences are elicited (Georgiev, 2017, 2020); for example, dolphins' double sonar experience of reflected ultrasound waves used for hunting prey or orientation in their natural habitat (Starkhammar et al., 2011; Branstetter et al., 2012; Jensen et al., 2013; Ridgway et al., 2015; Ladegaard et al., 2019). But this is the most we can do. We are unable to describe in words and communicate to others what it is like to have those experiences. Thus, conscious experiences are fundamentally *unobservable* and their phenomenal qualia are *incommunicable* (Georgiev, 2020). Since we have direct access to our own conscious experiences, we know that there is at least one conscious entity in the physical universe. From our shared evolutionary ancestry with other humans or animal species (Darwin, 2006; Dawkins, 2004; Stringer and Galway-Witham, 2017; Hublin et al., 2017; Chan et al., 2019), we also have solid scientific grounds to maintain that we are not the only conscious entity in existence. Therefore, the primary aim of a physical theory of consciousness is to provide criteria that

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will allow unambiguous specification of which physical systems are conscious and which are not. Once the conscious mind is physically identified, the physical laws will regulate how the mind affects the world (Georgiev, 2017). It should be noted that *consciousness*, *conscious experience*, *conscious state*, *mental state* and *mind* are used interchangeably throughout this work. A *mental process* (*conscious process*) is a process that involves a sequence of mental states (i.e. dynamically changing conscious experiences).

The seat of the human mind is the *brain cortex*. Cortical electric activity is mainly due to excitation of principal pyramidal neurons, which comprise over 70% of all cortical neurons (Fig. 1). Pyramidal neurons were designated as the 'psychic cells' of the brain by the father of modern neuroscience Ramón y Cajal since their electric activities instantiate feelings (Goldman-Rakic, 2002). Substantial medical evidence supports a cohesive relationship between the brain cortical electric excitation and the conscious mind because direct electric stimulation of the brain cortex elicits sensations (Bosking et al., 2017b; Hiremath et al., 2017; Yoshor et al., 2007), whereas discrete cortical lesions impair cognitive abilities or change the way one experiences the world (Chen et al., 2017; Hadid and Lepore, 2017; Sajja et al., 2017; Lau and London, 2018). For example, direct electric stimulation of the visual cortex through implanted electrodes that deliver digitized signals captured by a camera is capable of restoring the vision in blind patients whose eyes were injured by trauma (Dobelle, 2000; Bosking et al., 2017a; Lewis and Rosenfeld, 2016), while various injuries to the occipital lobe of the cortex produce blindness (Hadid and Lepore, 2017; Chen et al., 2017; Sajja et al., 2017). Apparently, the mind and the brain are not identical, because anesthetized brains do not generate conscious experiences. In the course of general anesthesia consciousness is erased by the pharmacological action of the anesthetic drug, yet the experimenter may stimulate with visible light the open eyes of anesthetized animals and still evoke electric potentials by pyramidal neurons located in the primary visual cortex (Lamme et al., 1998; Imas et al., 2005; Sellers et al., 2015; Hudetz and Imas, 2007). Similar experiments in anesthetized human subjects showed evoked electroencephalographic (McNeer et al., 2009) or electrocorticographic (Nourski et al., 2017) responses under auditory stimulation. If mind states were related to brain states through one-to-one correspondence (logical identity relation), it should not have been possible to turn mental states on or off using general anesthetics, because the brain states would have always remained mental states. Thus, the mind–brain problem is to explain how the unobservable conscious mind and the observable brain relate to each other: do they interact or does one unilaterally generate the other?

The unobservability and incommunicability of conscious experiences has been marshaled as evidence for the *nonphysical* nature of consciousness (Robinson, 1976; Jackson, 1982, 1986; Sprigge, 1994; Chalmers, 1995, 1996; Zhao, 2012) and the alleged inadequacy of physics to answer questions related to our mentality and sentience (Nagel, 1965; Kim, 1998; Campbell and Bickhard, 2011). Such a view is often grounded in the principles of *classical physics* according to which everything inside the physical world is observable, governed by deterministic physical laws, and causally closed in regard to its time dynamics with respect to non-physical entities (Susskind and Hrabovsky, 2013).

Classical reductionism fails because reductive identification of unobservable consciousness with observable physical properties is logically inconsistent. According to the postulates of classical physics (including classical mechanics, electromagnetism, and Einstein's theory of relativity) all existing things are physical and all physical entities are observable. In other words, by logical contraposition, it follows that if an entity is not observable, then it is not physical and does not exist. In the precise mathematical language of set theory, non-existing entities such as unicorns, centaurs or fairies, are all members of the empty set. Therefore, identifying the unobservable consciousness with any non-observable non-existing entity would be logically equivalent to classical eliminativism (Dennett, 1991) according to which consciousness does not exist

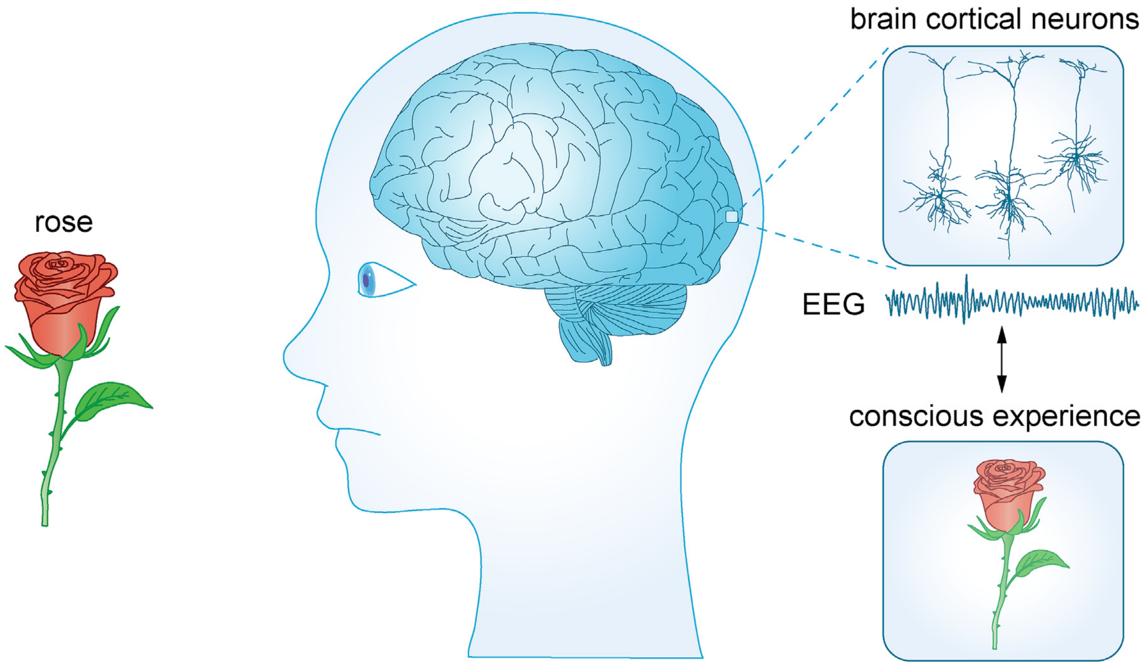

Fig. 1. The mind–brain problem. Neither the brain cortex whose anatomy can be observed during an open skull surgery, nor the cortical electric activity recorded by electroencephalography (EEG) resemble the visual conscious experience elicited by observation of a red rose. Explaining the physical relationship between the observable brain and the unobservable mind has troubled philosophers for centuries. Modified from Georgiev (2020).

and is a member of the empty set. Here, our goal is not to ban consciousness from existence, but to incorporate it into the physical description of the world.

The obstacles faced by classical reductionism compel many philosophers and neuroscientists to reject the postulate that all existing things are physical thereby assuming that the brain generates existing, but non-physical, non-observable conscious experiences, and consciousness is a functional product emerging out of the underlying brain activity (Fodor, 1981; Baars, 2005; Piccinini, 2010; Wenzel et al., 2019). Classical functionalism, however, also fails due to the closure of the physical world to non-physical entities. The conscious mind, if viewed as a functional product or an emergent property of the brain, can only be admitted as an *epiphenomenon* without any causal influence on physical events (Jackson, 1982), hence providing no basis for natural selection and no evolutionary advantage to conscious organisms in the fight for survival (Georgiev, 2013, 2019; Popper and Eccles, 1983). The adequate match between our conscious experiences, the neural responses, and the corresponding behavior, provides compelling evidence against epiphenomenalism. For example, the neural responses to detrimental factors are always associated with unpleasant feelings and avoiding behavior. If conscious experiences are causally effective, the evolution theory is able to explain the adequate matching between the unpleasant experiences, the avoiding behavior and the negative influence of detrimental factors upon the organism. Clearly, those animals that would have enjoyed detrimental factors would not have avoided dangers, thereby dying out in the competition with rival organisms. However, if conscious experiences were causally ineffective, the evolutionary explanation would fail since one would expect that in nature still there will be organisms that experience pleasant feelings when being injured but avoid detrimental factors due to the organization of their neural processes (James, 1879). Introspectively, we could verify that we never enjoy detrimental factors, hence epiphenomenalism and classical functionalism have to be false.

To avoid the charge of epiphenomenalism, consciousness has to be physical, thereby entering directly into the mathematical equations of the fundamental physical laws that describe the dynamics of physical systems endowed with conscious experiences. Certainly, this requires a fundamental revision of the principles of classical physics and incorporation of consciousness into a modern, non-classical physical theory. Fortunately, in 1920s the failure of classical physics to describe faithfully the physical world was well-established: it was unable to explain the stability of chemical atoms, the photoelectric effect, the electron diffraction in crystals and the spectral curve of blackbody radiation (Fayngold and Fayngold, 2013). The concerted efforts of quantum physicists have replaced the inadequate classical physics with a radically new, empirically successful, quantum theory based not only on different physical equations, but also on conceptually distinct quantum principles (Susskind and Friedman, 2014). Among the newly introduced concepts is the quantum indeterminism, which endows elementary particles with the *propensity to make choices* among different future possibilities available for actualization, and a dichotomy between what physically exists, described by unobservable quantum state vectors, and what can be physically observed, described by observable quantum operators. This dichotomy is crucial for addressing the mind–brain problem. Identifying the unobservable consciousness with the quantum information integrated in unobservable quantum brain state vectors makes consciousness causally effective in determining the probabilities for producing different quantum outcomes upon measurement. The observable brain then is nothing but the classical record of observed outcomes of brain quantum observables upon measurement with brain imaging devices (Georgiev, 2017).

In this present work, after briefly reviewing some preliminary background on the mind–brain problem to make the exposition self-contained, we will focus on the quantum information theoretic differences between the unobservable mind and the observable brain, and will elaborate on the Holevo bound, including its explicit mathematical formulation and the physical conditions that maximize its value to n bits of classical information for a system composed of n qubits.

2. Classical information-theoretic approach to the mind-brain problem

Even though quantum physics superseded classical physics a century ago, current neuroscience is still based solely on classical principles. This conservative approach denies any essential role of quantum effects in regard to consciousness and assumes that the brain processes related to the input, processing, storage and output of classical information are sufficient to explain consciousness. Limiting quantum theory to a narrow domain where quantum physical systems exhibit classical behavior, however, leads again to classical functionalism, epiphenomenalism, and the infamous hard problem of consciousness (Chalmers, 1995).

The characteristic features of classical behavior are the observability and communicability of classical information, and deterministic time evolution of physical states (Susskind and Hrabovsky, 2013). Classical information encoded onto a physical carrier can be *read* and *copied* onto a new carrier. If in the process of copying the old copy is preserved intact, classical information can be *multiplied*. Changing the nature of the physical carriers (e.g. from massive electrons to massless photons) allows classical information to be *broadcast* to a distant receiver where it is *recorded* and *stored*. The obtained classical information can be further *processed* using irreversible logic gates and/or *erased*. An illustrative example of classical information is the digital string of bits, 0s and 1s, which encodes a text file on a computer hard disk drive. One can display the text on a monitor and read it, copy the information contained in the digital file multiple times, or even erase the file in order to free hard disk memory space (Georgiev, 2013). Thus, the physical properties of classical information are ideal for memory storage and retrieval, namely, once memory traces are formed in the brain, they can be read again and recalled at a later time. Observable classical information, however, cannot lead to unobservable conscious experiences without assuming some form of functional emergence.

Functionally, neurons encode and transmit classical information in terms of electric spikes. Neuronal electric activity is due to ionic fluxes through excitatory or inhibitory ion channels incorporated in the excitable plasma membrane. Instrumental for most neurophysiological processes are sodium (Nav), potassium (Kv) and calcium (Cav) voltage-gated ion channels, selectively conducting Na^+, K^+ or Ca^{2+} ions down the respective ion concentration gradients (Georgiev and Glazebrook, 2014). The voltage sensing is performed by an electrically charged 4th α-helix inside each domain of the α-subunit of ion channels (Fig. 2). Macroscopic electric currents flow through a rich repertoire of neuronal voltage-gated ion channels, whose opening is regulated by the local voltage across the plasma membrane (Georgiev, 2015). As a result, the transmembrane voltage of neurons undergoes dynamical changes in time. Pyramidal neurons stay at rest if the transmembrane voltage in the soma and the axon initial segment does not exceed a threshold value of about -55 mV (Gasparini et al., 2004). When the voltage threshold is reached, the neuron fires a brief electric spike that propagates down the axon in order to activate synapses innervating other target neurons. Glial cells, including astrocytes and oligodendrocytes, maintain homeostasis of electrolytes and other biologically active substances in the brain, thereby nourishing and

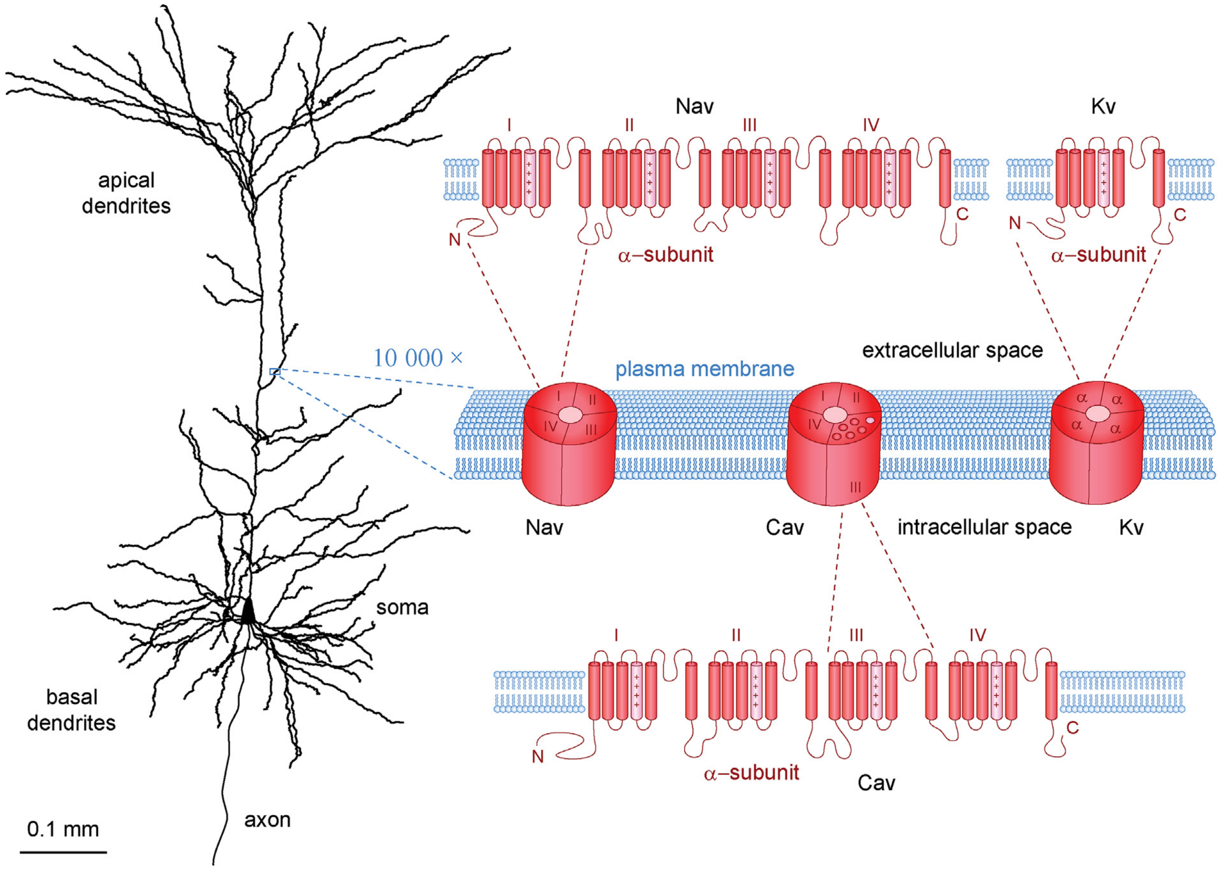

Fig. 2. Morphology of a cortical pyramidal neuron (NeuroMorpho.org NMO_09565) with structural representation of voltage-gated ion channels in a patch of the electrically excitable plasma membrane. The pyramidal neuron receives excitatory or inhibitory synaptic inputs applied at the apical and basal dendrites or the soma. If the summated synaptic electric currents depolarize the axon initial segment over the threshold value of −55 mV, the neuron discharges an action potential, which propagates down the axon and initiates the release of neurotransmitter from terminal axonal boutons onto target neurons. The electric activity of the neuron is mainly driven by ionic fluxes through sodium (Nav), potassium (Kv) and calcium (Cav) voltage-gated ion channels. Individual Nav and Cav channels are composed of α-subunits with four protein domains (I–IV) each, whereas Kv channels have disjoint protein domains into separate α-subunits. Each transmembrane channel domain is formed by six α helices bundled in parallel. The electrically charged voltage sensor that gates the ion channel is located within the 4th α-helix of each domain. Modified from Georgiev and Glazebrook (2014).

nurturing the easily vulnerable neurons (Verkhratsky and Nedergaard, 2017). With the use of electric spikes propagating within the neural network, the brain is able to perform a variety of computational tasks. Yet, the hard problem of consciousness is to explain why neuronal computation in the brain generates any conscious experiences at all (Chalmers, 1995).

The hard problem of consciousness is a hallmark of functional theories of consciousness, in which conscious experiences are assumed to be generated by the brain in the process of performing a certain kind of classical function. Once the function is precisely specified, e.g. neuronal computation, it becomes impossible to explain why it is the case that the brain does not operate in a mindless, nonconscious mode where the neurons perform the specified function without any generation of conscious experiences. Thus, the hard problem is an excellent test for epiphenomenal consciousness, namely, if the dynamics can be fully specified in advance without any reference to consciousness, then the generated conscious experiences have to be causally ineffective (Georgiev, 2017). Noteworthy, the hard problem does not occur for reductive theories of consciousness, in which conscious experiences are identified with physical states. Indeed, if the logical identity relation makes the mind equivalent to some physical state Ψ, it will be inconsistent to define alternative physical worlds in which the state Ψ is not a mind.

3. Quantum information-theoretic approach to the mind-brain problem

Quantum information is a novel kind of information that is held in the quantum states of quantum physical systems. Quantum information cannot be converted to classical information, which means that it is not contained in the mathematical description of a quantum physical state Ψ, but it is held in the physically existing substrate signified by Ψ. In other words, exactly as the *map* is not the *territory*, the quantum physical state Ψ of, say, an electron written as a mathematical symbol on a sheet of paper is not the same as the quantum state of the electron in the quantum physical reality. This needs to be properly understood if one is to overcome the possible discomfort resulting from staring at quantum mechanical expressions for Ψ while deriving mathematically, for example, that Ψ is not observable (Georgiev, 2017).

Quantum information differs from classical information in a number of striking ways, which we will briefly review using Dirac's bra-ket notation (Dirac, 1967). The two main quantum physical laws are given by the *Schrödinger equation* (Hayashi et al., 2015), which governs what physically exists and how it changes in time, and the *Born rule* (Busch et al., 2016), which governs what can be observed or measured with physical devices.

Schrödinger equation. The fabric of physical reality is woven from quantum probability amplitudes, which define the physical state of closed quantum physical systems obeying the Schrödinger equation

$$\imath\hbar\frac{\partial}{\partial \mathrm{t}}|\Psi(\mathbf{r},\mathrm{t})\rangle = \widehat{\mathrm{H}}\,|\Psi(\mathbf{r},\mathrm{t})\rangle \tag{1}$$

where $\imath$ is the imaginary unit, $\hbar$ is the reduced Planck constant, $\frac{\partial}{\partial t}$ is the partial time derivative operator, $|\Psi(\mathbf{r},t)\rangle$ is the quantum wavefunction, $\mathbf{r} = (x,y,z)$ is the vector of position coordinates, t is time, and $\widehat{H}$ is the Hamiltonian operator corresponding to the total energy of the quantum system (Georgiev, 2017, 2020).

The quantum wavefunction $|\Psi(\mathbf{r},t)\rangle$ of the physical system, which solves the Schrödinger equation, is a continuous distribution in three-dimensional space. As a consequence of the linearity of the Schrödinger equation, it follows that any two solutions $|\Psi_1(\mathbf{r},t)\rangle$ and $|\Psi_2(\mathbf{r},t)\rangle$ can be linearly superposed to form a new solution

$$|\Psi_s(\mathbf{r},t)\rangle = \alpha_1|\Psi_1(\mathbf{r},t)\rangle + \alpha_2|\Psi_2(\mathbf{r},t)\rangle \tag{2}$$

where α_1 and α_2 are complex numbers satisfying the normalization condition $|\alpha_1|^2 + |\alpha_2|^2 = 1$. Due to the principle of quantum superposition, the quantum wavefunction $|\Psi(\mathbf{r},t)\rangle$ has the properties of a vector (and behaves like a vector) in an abstract Hilbert space (Georgiev and Cohen, 2018).

Born rule. The value of the quantum wavefunction at a certain location $(\mathbf{r},t)$ in space and time is a complex number $\Psi(\mathbf{r},t)$ known as quantum probability amplitude (Feynman, 1948, 2014; Feynman et al., 2013). According to the Born rule, the absolute square of the quantum probability amplitude $|\Psi(\mathbf{r},t)|^2$ determines the quantum probability for some physical event involving the quantum system of interest to occur at the location with coordinates $(\mathbf{r},t)$. Importantly, the behavior of the quantum system is inherently indeterministic. If the exact state $|\Psi(\mathbf{r},t)\rangle$ of the quantum system is known through meticulous preparation (post-selection), the quantum probabilities for occurrence of different physical events (observations) will still arise, not because of our ignorance of what the quantum state is, but due to the inherent propensity of the quantum system to generate the observed outcomes under experimental measurement. Even though the quantum physical laws may preclude prediction with absolute certainty of the future state (or event) of a quantum system, they allow calculation of the probability for a given future state (or event) to be actualized by the system. As a consequence of indeterminism, consciousness does not have to be epiphenomenal in a quantum world and the origin of free will could be recognized in the process of actualization of physical events compliant with the Born rule (Georgiev, 2013, 2017).

The main characteristic property of the quantum wavefunction $|\Psi\rangle$ is that it is not observable. Of course, here we do not mean that the mathematical symbol $|\Psi\rangle$ typeset on paper is unobservable, but rather that the physical entity to which $|\Psi\rangle$ refers to in reality is unobservable. Exactly because the quantum information is fundamentally tied to its physical carrier, it is impossible for classical computers to replicate the behavior of quantum physical systems. While classical waves could be easily observed as ripples in a water tank, quantum waves are comprised from a contrastingly different fabric, namely unobservable quantum probability amplitudes (Georgiev, 2020). Observable physical quantities during a quantum measurement are the eigenvalues of some quantum operator (observable) $\widehat{A}$, which is represented by a matrix (Dirac, 1967; Fayngold and Fayngold, 2013; Susskind and Friedman, 2014; Hayashi et al., 2015). The quantum observable $\widehat{A}$ may operate upon any quantum wavefunction and generate another quantum wavefunction (Holevo, 2001). Of special physical interest is the set of eigenvectors of $\widehat{A}$ such that the action of $\widehat{A}$ on an eigenvector $|\Phi\rangle$ returns the same eigenvector $|\Phi\rangle$ multiplied by a number λ referred to as an eigenvalue, namely $\widehat{A}|\Phi\rangle = \lambda|\Phi\rangle$ (Strang, 2016). In n-dimensional Hilbert space, the quantum observable $\widehat{A}$ will have n orthogonal eigenvectors $|\Phi_1\rangle, |\Phi_2\rangle, \ldots, |\Phi_n\rangle$, each of which will be associated with a corresponding eigenvalue, $\lambda_1, \lambda_2, \ldots, \lambda_n$. The eigenvectors and eigenvalues of quantum observables play a major role in the process of quantum measurement as they are exhibited as measurement outcomes. Suppose that at time t we measure a quantum system whose quantum state is

$$|\Psi(t)\rangle = \widehat{I}|\Psi(t)\rangle = \sum_n |\Phi_n\rangle\langle\Phi_n|\Big|\Psi(t)\rangle = \sum_n \alpha_n\Big|\Phi_n\rangle \tag{3}$$

where $\widehat{I}$ is the identity operator and $\alpha_n = \langle\Phi_n|\Psi(t)\rangle$ are complex coefficients (Georgiev, 2020). For the quantum measurement of the observable $\widehat{A}$, the outcome could only be one of the eigenvalues present in the set $\{\lambda_1, \lambda_2, \ldots, \lambda_n\}$, after which the quantum system will collapse into the eigenvector corresponding to the obtained eigenvalue. For example, if the eigenvalue λ_n is obtained, immediately after the measurement at time t' the quantum system will turn into the state $|\Psi(t')\rangle = |\Phi_n\rangle$. The probability to obtain the particular eigenvalue λ_n is determined by the Born rule as the absolute square of the inner product between the initial quantum state $|\Psi(t)\rangle$ and the final quantum state given by the corresponding eigenvector $|\Phi_n\rangle$, namely

$$\mathrm{Prob}(\lambda_n) = |\langle\Phi_\mathrm{n}|\Psi(\mathrm{t})\rangle|^2 \tag{4}$$

In other words, the very act of quantum measurement is intrusive and forces the measured system to react. This abrupt collapse $|\Psi(t)\rangle \rightarrow |\Phi_n\rangle$ provides some insight into the origin of unobservability of the quantum wavefunction $|\Psi(t)\rangle$, namely the measurement of a quantum observable $\widehat{A}$ transforms probabilistically the measured system into an eigenvector $|\Phi_n\rangle$ of the measured observable. As a result, the external observer may learn the quantum state $|\Phi_n\rangle$ after the measurement, but is unable to reconstruct with certainty what the quantum state $|\Psi(t)\rangle$ of the measured system was before the measurement (Georgiev, 2017).

As a highlight of our brief excursion into quantum foundations, we could say that quantum states are vectors $|\Psi\rangle$, whereas quantum observables are operators $\widehat{A}$ in Hilbert space. This mathematical distinction results in a *schism* between what physically exists and what can be physically observed. The failure of naive realism, which identifies what is observed with what exists, allows quantum theory to accommodate conscious experiences that are subjective, private and inaccessible to observation.

Thomas Nagel has been able to nicely illustrate in a thought experiment the inner privacy of conscious experiences by examining the taste of chocolate (Nagel, 1987): suppose that an awake patient is undergoing an open skull neurosurgery with local anesthesia while eating chocolate. The surgeon will be able to directly see the soft, spongy substance of the patient's brain, and if a microscope equipped with sophisticated patch-clamp device is used, electrical recordings from individual neurons would reveal a chain of complicated physicochemical processes. Nonetheless, the surgeon would find nowhere the taste of chocolate, because the patient's conscious experiences are unobservable. In fact, conscious experiences are inside the mind with a kind of insideness that is quite unlike how the brain is inside the skull (Nagel, 1987).

In classical physics, the reductive approach to consciousness is unsuccessful because the unobservable conscious mind cannot be identified with an observable physical subsystem of the brain. In quantum physics, however, the conscious mind could be reductively identified with the quantum information integrated in some quantum state of the brain $|\Psi\rangle$ because both are unobservable. In this case, the unobservable conscious mind $|\Psi\rangle$ will not be a functional product of the observable brain $\widehat{A}$ that could be investigated with brain imaging devices. Instead, the situation will be reversed—the observable brain $\widehat{A}$ will be the product (classical record) of actualized mind decisions (choices) (Georgiev, 2017).

The temporal dynamics of quantum states governed by the Schrödinger equation has an important implication for the dynamic timescale of conscious processes. The total energy of the quantum system is given by the eigenvalues E_n and eigenstates $|E_n\rangle$ of the Hamiltonian operator $\widehat{H}$, namely $\widehat{H}|E_n\rangle = E_n|E_n\rangle$. For each eigenstate with definite energy, the Schrödinger equation generates solutions of the form

$$\Psi_n(t)\big|E_n\rangle = \Psi_n(0)e^{-\imath\,\omega_n\,t}\big|E_n\rangle \tag{5}$$

The angular frequency $\omega_n = E_n/\hbar$ of each solution $\Psi_n(t)|E_n\rangle$ establishes the quantum dynamic scale (period) of the process $t_n = 2\pi/\omega_n$ with which the wavefunction $\Psi_n(t)$ rotates inside the Hilbert space. For biomolecular energies exceeding the energy of thermal fluctuations $E \geq k_B T$, the dynamic timescale is

$$t \leq \frac{2\pi\hbar}{k_B T} \tag{6}$$

where k_B is the Boltzmann constant, and T is the temperature. At physiological temperature $T = 310$ K, the dynamic timescale is faster than 0.15 ps, which is in the realm of quantum chemistry. Thus, the dynamic timescale of conscious processes is consistent with picosecond conformational transitions of neural biomolecules (Georgiev and Glazebrook, 2007). Examples of picosecond protein dynamics, which is directly related to the neuronal processing of information, include regulation of conductance of voltage-gated ion channels (Callahan and Roux, 2018), activation of ionotropic glutamate receptors by neurotransmitter binding (Kubo et al., 2004), or vibrational motions of the α-helix backbone involved in the conformational flexibility of SNARE proteins that drive exocytosis of synaptic vesciles (Stelzer et al., 2008). In contrast, the observable brain dynamics of electric spikes propagating along neuronal projections at a millisecond timescale describes transfer of classical information, which is triggered by quantum processes, but sets no lower bound on how fast these quantum processes are.

4. Physical properties and theoretical utility of quantum information

Quantum information theory has been able to distill the main properties of quantum information into a number of no-go theorems (Nielsen and Chuang, 2010; Pathak, 2013; Hayashi et al., 2015). Unknown quantum states that are not prepared by us cannot be read (cannot be unambiguously reconstructed from measurements) (Busch, 1997), cannot be cloned (multiplied) (Wootters and Zurek, 1982), cannot be deleted (Pati and Braunstein, 2000), cannot be broadcast (Barnum et al., 1996), and cannot be converted into a string of bits of classical information, even if an infinite string of classical bits were allowed (Pathak, 2013). Bell's theorem further shows that quantum entangled states of composite quantum systems exhibit nonlocality, which can only be explained by the admission of superluminal action at a distance between the spatially separated quantum components (Aspect, 1999; Georgescu, 2014; Rosenfeld et al., 2017). These physical properties of quantum information are able to address different aspects of consciousness.

The *unobservability* of quantum information is able to protect the inner privacy of conscious experiences against external peering with alleged mind-reading devices (Georgiev, 2017). This means that we may keep secrets in our mind insofar we do not verbalize them in words. Because our inner monologue is expressible as a string of classical bits of information, we should be aware that the neural electric signals corresponding to individual words are subject to eavesdropping, even before the words are spoken in the form of audible acoustic waves.

The *nonclonability* of quantum information is able to protect the identity of the self against possible duplication at a different location in space (Georgiev, 2017). Being macroscopically localized ensures the historicity of the self and underlies our perception of being embodied. Knowing that we cannot be clones of another conscious being also provides us with an insurance against external blackmailing with alleged torture of multiple brain-in-a-vat clones of ourselves, which are supposed to have conscious experiences indistinguishable from ours (Elga, 2004). Classically, we may doubt whether we are the genuine original or a clone, whereas in a quantum world, we may rest assured that we are physically unique.

The *inconvertibility* of quantum information into classical information is able to explain why we cannot communicate the phenomenal qualia of our experiences (what it is like to feel what we experience) to others (Georgiev, 2017). Suppose that in an imaginary world our conscious experiences were communicable. In such a world, we would have been able to restore missing senses through transmission of classical strings of bits, 0s and 1s, which comprise the digital files of textual or audiovisual material. For example, we would have been able to make a blind person see a visual scenery by simply describing it with our words (Georgiev, 2017, 2020). Effectively, blindness would have been cured through genuine visual experiences elicited by words. Unfortunately, this is not our world. Nonetheless, existing regularities within our conscious experiences can be communicated to other people. Conscious experiences can be categorized into distinct categories: familiar or unfamiliar, pleasant or unpleasant, etc. Such categorization is expressible in classical bits of information. In fact, classical information can be used for the preparation of a set of orthogonal (distinguishable) quantum states. This may provide a possible explanation of why we do not continuously experience stored memories but need a recall in order for certain memories to be consciously relived, namely our memories are nothing but classical instructions of how to bring back the quantum brain in a certain quantum state selected from an orthogonal set of states.

The *inerasability* of quantum information is able to protect against external hindering with one's causal potency or free will (Georgiev, 2017). Classical deletion works by taking different input classical states and deterministically preparing them in a certain output state designated to be the empty state (Shen et al., 2011). Different quantum states, however, produce probabilistic outcomes upon measurement, and there is no general unitary operation that could transform all possible input quantum states into the same empty quantum state. This means that the preparation of a desirable quantum state is always a post-selection, namely, the quantum system chooses a measurement outcome in accordance with inherent propensities given by the Born rule, and then the external observer chooses to work with only those quantum systems that have produced a certain desirable outcome. It should also be noted, that future quantum choices are not dependent on past quantum choices. For example, a single electron can be prepared multiple times in an initial state $|\uparrow_z\rangle$ such that the electron spin points up along the z-axis, after which the electron spin can be measured along the x-axis. For each of these measurements, there will be an equal probability for the spin to point up $|\uparrow_x\rangle$ or down $|\downarrow_x\rangle$ along the x-axis, regardless of what the sequence of previous measurement outcomes for the x component of spin is.

The *nonlocality* of quantum information due to quantum entanglement is able to explain the combination problem (binding problem) of conscious experiences (Georgiev, 2017). Indeed, while the reductive solution to the mind–brain problem avoids the charge of epiphenomenal emergence by attributing elementary conscious experiences to all matter, it requires a mechanism by which elementary conscious experiences could combine together and unite into larger, more complex, and ultimately human-like conscious minds (Basile, 2010; Coleman, 2012; Morris, 2017). Quantum entanglement provides the physical mechanism by which the quantum probability amplitudes of component quantum systems become inseparable (Horodecki et al., 2009; Peled et al., 2020; Gudder, 2020). As an example, consider the singlet state composed of two entangled spin-$\frac{1}{2}$ particles given by a composite state vector

$$\left|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_A|\downarrow\rangle_B - |\downarrow\rangle_A|\uparrow\rangle_B\right)\right. \tag{7}$$

where neither the particle A, nor the particle B has its own separable state vector. However, if the composite state of particles A and B can be expressed as a tensor product state

$$|\Psi\rangle_{AB} = |\Psi\rangle_A \otimes |\Psi\rangle_B \tag{8}$$

then both particles A and B will have their own individual state vectors such that

$$|\Psi\rangle_A = a_1|\uparrow\rangle_A + a_2|\downarrow\rangle_A \tag{9}$$

$$|\Psi\rangle_B = b_1|\uparrow\rangle_B + b_2|\downarrow\rangle_B \tag{10}$$

where the complex quantum probability amplitudes are normalized $\sum\left|a_i\right|^2 = \sum\left|b_i\right|^2 = 1$.

In the tensor product state $|\Psi\rangle_A \otimes |\Psi\rangle_B$, it is not only that the particles A and B have their own state vectors $|\Psi\rangle_A$ and $|\Psi\rangle_B$, but the composite system also has a state vector $|\Psi\rangle_{AB}$.

If the quantum information contained in the state vector is to be identified with the mind of the system, to avoid paradoxical existence of minds within other minds it has to be specified that only state vectors that cannot be expressed as tensor products correspond to *individual minds*. If a state vector can be expressed as a tensor product, then it will correspond to a *collection of separate minds*. Thus, by decomposing the quantum state $|\Psi\rangle_U$ of the universe into a tensor product form

$$|\Psi\rangle_U = |\Psi\rangle_1 \otimes |\Psi\rangle_2 \otimes \ldots \otimes |\Psi\rangle_k \tag{11}$$

quantum information theory provides a theoretical rule that explicitly specifies the boundaries of individual minds $|\Psi\rangle_k$ in a universal complex-valued Hilbert space (Georgiev, 2017). The combination of conscious experiences through quantum entanglement also elaborates on the free will theorem by Conway and Specker (Conway and Kochen, 2006, 2009) by showing that elementary quantum particles possess free will that allows them to produce contextual outcomes upon different quantum measurements but only as long as they are in a separable tensor product state (Georgiev, 2017). Otherwise, if the elementary quantum particles enter into a composite entangled state, it is the composite system that manifests free will, not the individual components whose measurement outcomes have to be nonlocally correlated. In order to avoid quantum entanglement of the whole universe into a single universal cosmic mind, the reductive quantum information theoretic approach to consciousness requires the existence of a non-unitary physical process of objective reduction with associated disentanglement of macroscopic quantum physical systems that have attained a certain energy threshold [for details see Chapter 6 in Georgiev (2017)].

The reductive identification of the quantum information contained in the quantum probability amplitudes Ψ with consciousness leads to quantum panpsychism. This means that mentality in the form of primitive subjective conscious experiences is attributed to all matter in the quantum universe. In other words, consciousness does not emerge at some later stage in the history of the universe, but is already present in the quantum probability amplitudes Ψ of all quantum particles at the very origin of the universe. Here, it is important to emphasize that there is no single cosmic conscious mind permeating the universe, but a stochastic collection of fleeting minds popping in and out of existence. Consider as an example, liquid water near thermodynamic equilibrium. Thermal noise leads to vibrational motion of water molecules, but does not prevent the formation of water clusters such as hexamer prisms or cages $(H_2O)_6$ through hydrogen bonding (Foley and Mazziotti, 2013; Richardson et al., 2016). The hydrogen bonds share quantum entanglement (Pusuluk et al., 2018) between water molecules, which would then imply the existence of fleeting minds for each entangled cluster $|\Psi_k\rangle$ present in Eq. (11). These brief moments of subjectivity in the individual entangled water clusters would last only for a few picoseconds (Elgabarty et al., 2020) before the water clusters are destroyed by the thermal noise. Because such fleeting minds in nonliving matter possess no memory and no means for communication with the surrounding world, they lack many of the features that we attribute to human consciousness. In the presence of interfaces provided by lipid membranes or protein biomolecules, however, water molecules can form extended hydrogen bond networks (Paciaroni et al., 2008; Fayer, 2012; Stöhr and Tkatchenko, 2019) whose interfacial orientational relaxation timescale of 18 ps is almost an order of magnitude larger compared with the relaxation time of 2.6 ps in bulk water (Fayer, 2012). This already illustrates how the presence of biomolecules supplies a form of ultrafast memory for thin layers of interfacial water. To build a fully functional mental unit for the human mind, natural selection had to assemble electrically excitable neurons from phospholipid membranes, proteins, signaling biomolecules, interfacial water and electrolytes, which collectively not only support complex entangled quantum states, but could also store long-term memories of those quantum states and use past memories to react to environmental stimuli.

5. Molecular mechanisms of human consciousness

The proposed quantum information-theoretic approach to the mind–brain problem is reductive in nature and identifies quantum information contained in quantum probability amplitudes with *experiences*. This endorses a form of quantum *panpsychism* or *panexperientialism*, namely all quantum particles posses some elementary experiences that need to be organized through natural evolutionary processes in the proper way to compose a human mind that has a sense of “self” and is capable of rational thinking. In humans, the brain cortex is the seat of consciousness and normally there is only one dominant personality, which we experiences as our conscious “I”. In certain abnormal cases, however, a single brain can contain several minds, which may or may not be aware of each other’s existence (Georgiev, 2017). For example, in split-brain patients who had their corpus callosum surgically severed in order to treat refractory epilepsy, each of the two cortical hemispheres hosts a separate mind that could communicate individually and control a half of the body apparently unaware of the other mind in the opposite hemisphere (Gazzaniga et al., 1962; Sperry, 1966, 1982; Gazzaniga and Sperry, 1967; Gazzaniga, 2002; Wolman, 2012). In psychiatric disease, such as dissociative identity disorder (also known as multiple personality disorder) a single brain may contain a number of different minds that take control over the body in succession (Gillig, 2009). The possible existence of multiple minds inside a single brain is hard to explain classically, but it is a natural prediction of quantum panpsychism. In normal conditions, a healthy dominant conscious "I" residing in the brain cortex will not be aware of the existence of conscious experiences in other subcortical areas of the brain. Thus, from the viewpoint of the conscious "I", what is going on in the subcortical areas could be called "subconsciousness", but qualitatively these will be experiences to which the conscious "I" has no concurrent access. In the rest of this section, we will focus on molecular mechanisms whose quantum dynamics in the brain cortex may be characteristic for the realization of human consciousness expressed through the conscious "I".

The main thrust of quantum information theory is to conceptualize the differences between classical and quantum physical behavior and distill those differences into explicit no-go theorems (Pathak, 2013; Nielsen and Chuang, 2010). The application of quantum information-theoretic results to brain physiology, however, requires underlying biomolecular substrates that exhibit quantum behavior. Recent advances in the methods for solving numerically the Schrödinger equation allow *ab initio* studies of quantum physical systems composed of several thousand atoms (Sholl and Steckel, 2009; Ullrich, 2012; Helgaker et al., 2013; Su and Xu, 2017). So far, computational quantum chemistry has provided evidence for dynamic quantum effects in biomolecule-ion interaction (Kolev et al., 2013, 2018), enzyme catalysis (Ishida et al., 2006; Ranaghan and Mulholland, 2017; Sousa et al., 2016), ion channel gating (Bucher et al., 2010; Bucher and Rothlisberger, 2010; Kariev et al., 2007, 2014; Kariev & Green, 2009, 2019, 2012; Roy and Llinás, 2009; Maffeo et al., 2012; Flood et al., 2019), and protein-induced remodeling of phospholipid membranes (Ingólfsson et al., 2016). Quantum tunneling in the gating of voltage-gated ion channels (Chancey et al., 1992; Vaziri and Plenio, 2010; Kariev and Green, 2019) or zipping of SNARE (soluble N-ethylmaleimide-sensitive factor attachment protein receptor) proteins in neurotransmitter release (Georgiev and Glazebrook, 2018) may act as a quantum trigger whose effects are amplified into macroscopic patterns of electric activity of the cortical neural network.

Quantum effects inside the pores of ion channels confer selectivity for passage of a certain type of ion (Bucher et al., 2010; Bucher and Rothlisberger, 2010; Kariev et al., 2007, 2014; Kariev & Green, 2009, 2019, 2012). Ion selectivity divides channels into excitatory or inhibitory. Sodium and calcium channels excite the neuron because they let positively charged Na^+ and Ca^{2+} ions, respectively, enter into the cytosol. Conversely, potassium channels inhibit the neuron, as they let positively charged K^+ ions escape from the cytosol toward the extracellular space. At places where positively charged ions enter the neuron, the electric voltage across the membrane increases and the membrane depolarizes. Alternatively, if positively charged ions leave the neuron, the electric voltage decreases and the membrane hyperpolarizes. Both depolarizations and hyperpolarizations spread along the neuronal projections and summate at the axonal hillock where electric spikes are generated. The quantum behavior of individual voltage-gated ion channels is manifested in the binary dynamic change of their electric conductance: the open channel selectively conducts ions with a characteristic picosiemens single channel conductance, whereas the closed channel does not conduct at all. At a given value of the transmembrane voltage of the neuron, individual voltage-gated ion channels undergo stochastic (probabilistic) transitions between closed and open states (Sakmann and Neher, 1995). When the voltage across the neuronal plasma membrane is far away from the threshold for generation of an electric spike, the neuronal activity is not particularly sensitive to the tiny stochastic fluctuations in the transmembrane potential due to single channel transitions between closed and open conformations (Georgiev, 2015). When the voltage is near to the threshold value of -55 mV, however, closing or opening of a single ion channel may influence the generation of electric spike (Destexhe and Contreras, 2006). In the human brain cortex, there are $\approx 1.6 \times 10^{10}$ neurons (Azevedo et al., 2009) which could attain firing frequencies of ≈ 40 Hz. Thus, each millisecond thousands of cortical neurons may sense the closing or opening of a single channel and amplify its quantum dynamics into a macroscopically distinct electric firing pattern of the cortical neuronal network.

Sensory and somatomotor information encoded in electric spikes is reliably transmitted across the synapses of the sensory pathways from the sensory organs toward the brain cortex (Kim et al., 2013; Singer, 2007; Glowatzki and Fuchs, 2002; Magistretti et al., 2015) or the somatomotor pathways from the motor cortex toward the muscles (Kuno et al., 1971). To achieve reliability of transmission, the chemical synapses in these pathways release multiple synaptic vesicles upon depolarization of the presynaptic axonal boutons (Rudolph et al., 2015). The multivesicular release of neurotransmitter molecules then generates large postsynaptic currents in the target neuron (Rudolph et al., 2015). The reliable transmission of electric signals between the brain cortex and the body (Fig. 3) ensures the survival of the organism through the execution of fight-or-flight responses.

In contrast to extracortical synapses, individual synapses inside the brain cortex and the hippocampus were found to release either a single synaptic vesicle or none. Thus, each cortical synapse (Fig. 4) appears to possess only one functional release site at a given time (Stevens and Wang, 1995). The probability for release of neurotransmitter through synaptic vesicle exocytosis at intracortical synapses is 0.35 ± 0.23 per axonal spike (Dobrunz and Stevens, 1997). This means that an electrically excited axonal bouton is twice more likely to fail than succeed in releasing neurotransmitter. If it is conservatively estimated that each cortical neuron has only $n = 1000$ axonal boutons, and on average only $k = 350$ of these boutons release neurotransmitter per electric spike, the number of possible combinations given by the binomial coefficient $\frac{n!}{k!(n-k)!}$ for exocytosis per neuron is over 10^{279}. If the mind were not in control of synaptic vesicle release, the cortical neural network would have been disorganized within seconds (Georgiev and Glazebrook, 2018). Fortunately, recent advances in molecular neuroscience have revealed an elaborate protein machinery that regulates synaptic vesicle fusion with the active patch of presynaptic plasma membrane (Branco and Staras, 2009; Südhof, 2013).

The minimal molecular machinery capable of driving synaptic vesicle fusion is comprised of only three SNARE proteins: synaptobrevin, syntaxin and SNAP-25 (Fig. 5) (Weber et al., 1998). These three SNARE proteins zip together to form a bundle of four α-helices referred to as the core SNARE complex. The twisting of the 4-α-helix bundle inside the core SNARE complex applies a traction force that drives the fusion of the opposing phospholipid bilayers of the synaptic vesicle and the plasma membrane (Weber et al., 1998; Risselada and Grubmüller, 2012; Südhof, 2012, 2013; Zhou et al., 2015). The zippering of the core SNARE complex is potent enough to drive synaptic vesicle exocytosis even in neurons expressing artificially engineered lipid-anchored synaptobrevin and syntaxin molecules that lack their transmembrane regions (Zhou et al., 2013).

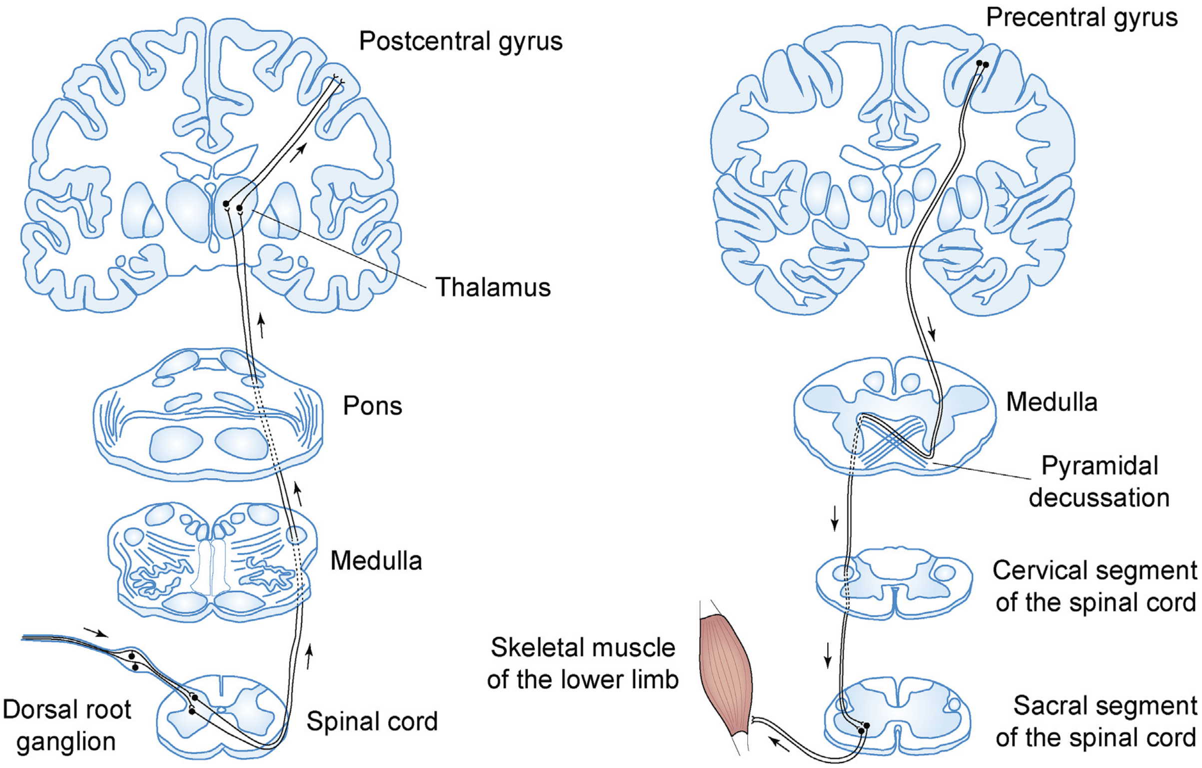

Fig. 3. Classical communication through electric signals between the brain cortex and the body. The somatosensory pathway (left) delivers sensory information from the body to the somatosensory cortex in the postcentral gyrus, whereas the somatomotor pathway (right) delivers motor information from the motor cortex in the precentral gyrus to the body muscles. The spinal cord segments, medulla and pons are represented with their transversal sections, whereas thalamus and cortex are shown in frontal slice. Modified from Georgiev (2017).

In different neuron types, the process of exocytosis is regulated by different sets of SNARE master proteins (Zhou et al., 2015; Rizo and Südhof, 2012; Südhof and Rothman, 2009; Giraudo et al., 2006) that effectively set the potential energy barrier for vesicle fusion. The potential energy $V(\mathbf{r})$ enters into the Hamiltonian

$$\widehat{H} = -\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}) \tag{12}$$

for the Schrödinger equation, where it constrains the motion of massive quantum particles with mass m. The motion of quantum particles is free inside spatial regions with zero potential energy, analogously to the classical case. However, there is a substantial difference between classical and quantum behavior for regions in which the potential energy is non-zero. Classical particles are forbidden from entering spatial regions where the particle energy is less than the potential energy, $E_0 < V(\mathbf{r})$, whereas quantum particles are not (Landau and Lifshitz, 1965). In fact, the quantum wavefunction $\Psi(\mathbf{r})$ needs to be continuous throughout space, which allows the quantum particle to tunnel through the potential energy barrier with height $V_0 > E_0$ and appear on the other side. In protein α-helices, quantum quasi-particles called Davydov solitons, which are composed of amide I excitation self-trapped in the lattice distortion of hydrogen bonded peptide groups, are able to transport energy along the protein and could trigger conformational transitions (Georgiev and Glazebrook, 2019,b, 2020b). Because the probability of release in intracortical synapses is less than one, the quantum mechanical description of the process involves quantum tunneling through potential barrier whose height is higher than the energy of quantum quasi-particle, presumably Davydov soliton, which triggers the release (Beck and Eccles, 1992; Georgiev and Glazebrook, 2012, 2019b).

The mass of the Davydov soliton is ≈5% of the proton mass and readily undergoes quantum tunneling (Georgiev and Glazebrook, 2020a). The Davydov soliton is a type of acoustic polaron formed by the interaction of excitons (C═O bond vibrations) with phonons (deformations of the hydrogen bonded lattice of peptide groups) inside protein α-helices. Because the protein backbone is quite massive (the average mass on an amino acid residue is 114 proton masses), the quantum motion of peptide groups (given by the generalized Ehrenfest theorem) is virtually indistinguishable from classical motion. Consequently, the protein backbone could be viewed as providing a potential energy landscape for the motion of the much lighter excitons. Through nonlinear feedback effect called *self-trapping*, the presence of the exciton, in turn, influences the motion of the hydrogen bonded peptide groups inducing *phonon dressing*. The combination of an exciton together with its phonon dressing is referred to as Davydov soliton. When a portion of the protein α-helix is embedded inside a phospholipid membrane or interacts with another protein, there is a resulting clamping action that constrains the motion of the α-helix thereby increasing locally its effective mass. The result of external clamps is that an exciton/soliton propagating along the α-helix would meet a massive barrier. Depending on the mass of the barrier, the exciton may be able to pass through the barrier employing quantum tunneling or may reflect from the barrier (Fig. 6). In the case of SNARE zipping, the role of the barrier is played by the Ca^{2+} sensor synaptotagmin, which clamps the SNARE complex in partially zipped conformation. Quantum tunneling of Davydov soliton through the barrier may induce full zipping of the SNARE complex and trigger exocytosis. In essence, massive proteins do not quantum tunnel, whereas quantum excitations propagating along the proteins do. Quantum

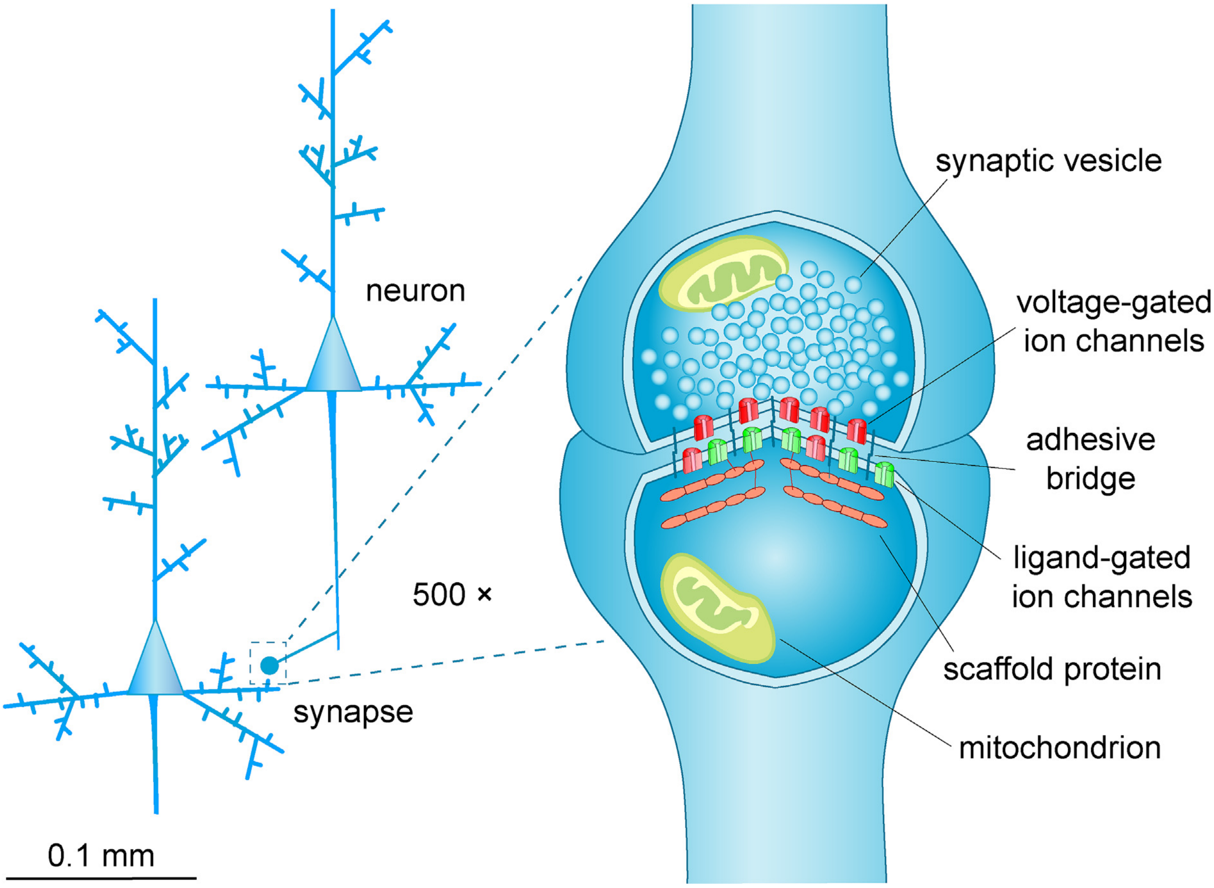

Fig. 4. Excitatory synaptic contact between pyramidal cortical neurons. The presynaptic axonal bouton has a pool of synaptic vesicles that contain neurotransmitter (glutamate). During an electric spike, the activation of presynaptic voltage-gated calcium channels initiates Ca^{2+} influx at the active zone, which may trigger fusion of a single synaptic vesicle with the plasma membrane. The released neurotransmitter (glutamate) acts on postsynaptic ligand-gated ion channels, such as AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) or NMDA (*N*-methyl-D-aspartate) receptors, to induce postsynaptic electric currents in the target neuron. Structural support for the synapse is provided by adhesive bridges and scaffold proteins, whereas mitochondria ensure robust energy supply for synaptic neurotransmission. Modified from Georgiev (2017).

tunneling of such excitations could act as a trigger that steers the overall protein motion at points of bifurcation into one of two alternative classical paths. Thus, cortical neurons that have surpassed with certainty the voltage threshold for the generation of electric spike, are able to amplify the quantum dynamics of SNARE proteins at individual axonal buttons into a macroscopic pattern of active synapses that release neurotransmitter molecules.

In summary, the dominant conscious “I” in the brain cortex is to be identified with the unobservable quantum information contained in the quantum state of quantum entangled membrane-bound proteins, including voltage-gated ion channels, ligand-gated ion channels and SNARE proteins, residing in the plasma membranes of millions of cortical neurons. The dynamic timescale of the underlying quantum processes is on the order of picoseconds, which addresses effectively previously noted issues with decoherence (Tegmark, 2000). The power of the thermal noise is both frequency and temperature dependent as given by the Johnson–Nyquist formula (Johnson, 1928; Nyquist, 1928)

$$P(f) = \int_{f_1}^{f_2} \frac{hf}{e^{\frac{hf}{k_B T}} - 1} df \tag{13}$$

where h is the Planck constant, f is the frequency, $\Delta f = f_2 - f_1$ is the bandwidth, k_B is the Boltzmann constant and T is the temperature. Thus, quantum effects readily persist not only for very low temperatures near absolute zero but also for very high frequencies over 1 THz. Psychophysical and clinical evidence from patients with time agnosia, which supports a submillisecond timescale of consciousness, has been extensively discussed in previous works (Georgiev, 2013, 2017).

To highlight the novel features of the quantum information theoretic approach to the mind–brain problem, it would be helpful to compare it with the orchestrated objective reduction (Orch OR) theory (Hameroff and Penrose, 2014) that also attempts to connect quantum mechanics to consciousness. Because the points of disagreement are substantial and somewhat involved, we will discuss each conceptual difference separately.

First, the two theories use the word “quantum” in mutually exclusive senses. In quantum information theory, the “quantum” characteristics of physical systems (wave-particle duality, superposition, interference, entanglement, tunneling) originate from compliance with continuous unitary dynamics according to the Schrödinger equation, whose solution is the quantum wavefunction Ψ. In the Orch OR theory, the main focus is on discrete non-unitary, non-computable violations of the Schrödinger equation induced by “quantum gravity”. Thus, the two theories disagree on whether conscious experiences are present during the continuous period of unitary dynamics according to the Schrödinger equation: the quantum information theory says yes, the Orch OR theory says no. Also, consciousness in the quantum information theory originates in the unitary dynamics, whereas consciousness

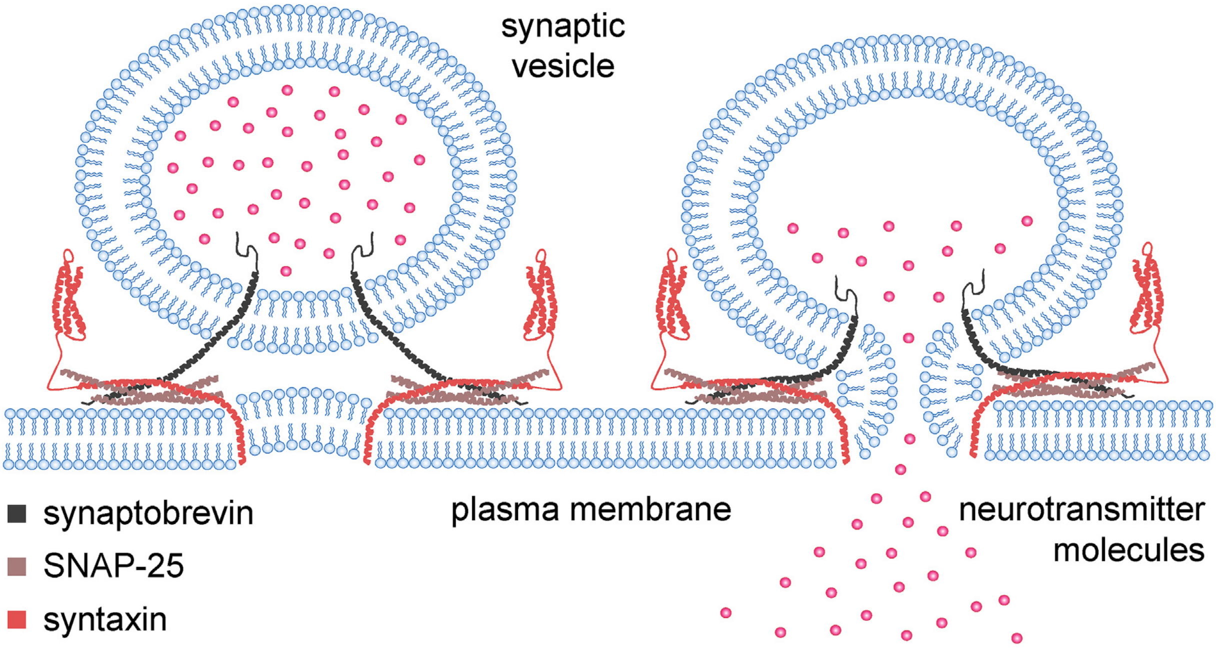

Fig. 5. Synaptic vesicle exocytosis driven by cooperative zipping of SNARE protein complexes. Initial docking of the synaptic vesicles at the active zone of the synapse is actuated by partially zipped SNARE protein complexes (left). Electric activity of the presynaptic terminal with its accompanying Ca^{2+} influx triggers full zipping of the SNARE complexes in a docked vesicle with subsequent opening of the fusion pore and extrusion of neurotransmitter from the synaptic vesicle into the synaptic cleft (right). Modified from Georgiev and Glazebrook (2014).

in the Orch OR theory originates in the non-unitary dynamics.

Second, the two theories assess the need of "emergence" with contrasting evaluations. In quantum information theory, the quantum wavefunction Ψ is reductively identified with the mind of the physical system. Therefore, conscious experiences originate as physical solutions Ψ of the Schrödinger equation and need no further physical laws to miraculously pop into existence emergent sentience from insentient matter. In the Orch OR theory, conscious experiences emerge in the form of discrete subjective "flashes", "bings", or "nows" from non-unitary, non-computable objective reduction events in the fundamental space-time geometry. The main problem with "emergence" is that it only postulates violation of the physical laws, but does not inform us about the properties of the emergent phenomenon. In contrast, the reductive identification of consciousness with Ψ implies that consciousness should necessarily possess all the physical characteristics that can be deduced from the Schrödinger equation.

Third, the two theories attribute distinct "causal efficacy" to consciousness. In quantum information theory, the absolute square of the quantum wavefunction $|\Psi|^2$ determines the probabilities for future courses of action. Therefore, if consciousness is Ψ, then it causally introduces biases in what future physical events can happen and how probable they are. Reduction of the wavefunction $\Psi \equiv \sum_i \Psi_i$ to a particular outcome Ψ_i upon quantum measurement, is then viewed as an act of choice making and manifestation of inherent free will by the quantum system, which already possesses consciousness. In the Orch OR theory, conscious experiences are generated by the non-computable objective reduction process, $\sum_i \Psi_i \rightarrow \Psi_i$, yet due to the physical closure of the world, the emergent consciousness becomes an epiphenomenon that only witnesses what has happened, but is causally ineffective to determine what can happen or will happen next. Natural selection and evolution of epiphenomenal consciousness is impossible.

Fourth, the two theories operate at different timescales and rely on different underlying biomolecular substrates. In quantum information theory, human consciousness operates at picosecond timescale and is supported by voltage-gated ion channels and other membrane-bound proteins incorporated in excitable neuronal membranes, which is consistent with the neural delivery of sensory information and output of motor information in the form of electric spikes. In the Orch OR theory, human consciousness operates at millisecond timescale and is supported by cytoskeletal microtubules, which are hypothesized to be isolated from the surrounding neural electric activities to prevent quantum decoherence, yet also somehow capable to control the generation of electric spikes at the axonal hillock. Fortunately, the discovery of general anesthetics provides an experimental framework for studying the molecular mechanisms of human consciousness through attempts to reversibly turn it off and on in clinical settings with human subjects.

6. The SNARE protein complex is main molecular target for volatile anesthetics

Pharmacological studies have shown that volatile anesthetics activate ligand-gated $GABA_A$ chloride ion channels (Garcia et al., 2010), and block voltage-gated sodium (Purtell et al., 2015) or calcium (Joksovic et al., 2009) ion channels. The increased sensitivity to volatile anesthetics conferred by the expression of mutant voltage-gated sodium channels (Pal et al., 2015), however, provides only indirect link to consciousness, and experimental attempts to introduce resistance to anesthesia in mice expressing artificially engineered mutant voltage-gated calcium channels (Petrenko et al., 2007) or volatile anesthetic-resistant $GABA_A$ chloride ion channels (Werner et al., 2011) have been unsuccessful. In contrast, several lines of experimental evidence point to direct involvement of SNARE proteins in volatile anesthetic-induced unconsciousness (Georgiev and Glazebrook, 2010). Firstly, general anesthesia with clinical concentrations of volatile anesthetics, such as isoflurane or halothane, inhibits excitatory neurotransmitter release (MacIver et al., 1996; Herring et al., 2009; Wu et al., 2004), and selectively

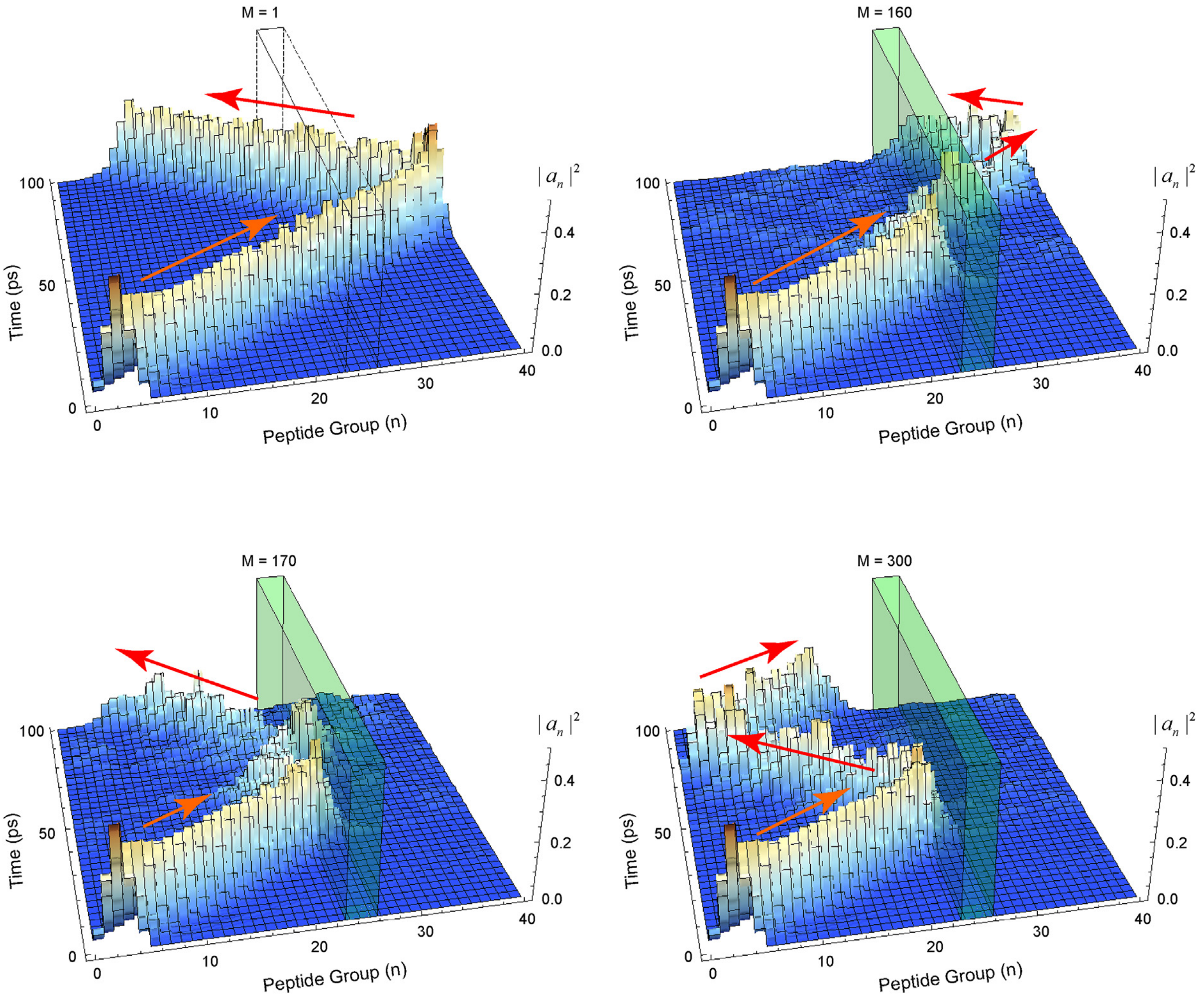

Fig. 6. Quantum dynamics of Davydov soliton visualized by the probability $|a_n|^2$ of finding the exciton at the peptide group n inside a hydrogen bonded protein α-helix spine simulated for 100 ps. In the absence of massive barrier ($M = 1$), the envelope of excition probabilities $|a_n|^2$ propagates as a solitary wave (soliton), which reflects from the ends of the protein α-helix. In the presence of massive barrier ($M = 160$) extending over 3 peptide groups $n = 22 - 25$, each of which with effective mass 160 times greater than the mass of an average amino acid residue, the soliton tunnels through the barrier with picosecond time delay. When the barrier mass is increased by only 6.25% to $M = 170$, the tunneling is drastically suppressed due to exponential decay of excition quantum probability amplitudes inside the barrier and the soliton cannot penetrate to the other side. For barrier with $M = 300$, the soliton bounces off the barrier resembling the elastic collision of a classical billiard ball with a wall. Red arrows help indicate the direction of motion.

erases consciousness, but not all cortical electric responses. In particular, electric potentials evoked by applied visual stimuli are routinely recorded from the visual cortex of anesthetized animals (Lamme et al., 1998; Imas et al., 2005; Sellers et al., 2015). Secondly, volatile anesthetics bind with high affinity to syntaxin either as a purified protein or as a component of the core SNARE complex (Nagele et al., 2005; Johansson et al., 2000). Thirdly, resistance to volatile anesthetics is conferred by a genetic mutation that results in the translation of a truncated form of syntaxin (van Swinderen et al., 1999). Animals with truncated syntaxin require higher doses of isoflurane for induction of anesthesia and also recover faster from anesthesia in comparison with wild-type animals (Troup et al., 2019). *In vitro* experiments further show that the expression of the truncated syntaxin in PC12 cells completely blocks the effects of isoflurane on the neurotransmitter release machinery despite the presence of endogenous syntaxin (Herring et al., 2009). Taken together, these findings support the aforementioned quantum model of neurotransmitter release in which volatile anesthetics inhibit quantum tunneling by raising the height of the potential energy barrier for SNARE protein zipping. Hence, the quantum quasiparticles (Davydov solitons) required for exocytosis are effectively isolated from their environment by being trapped in deep potential wells and their quantum states remain separable from the rest of the brain. According to the quantum information-theoretic approach to consciousness, it is quantum entanglement (as opposed to quantum separability) of component systems that binds conscious experiences together (Georgiev, 2017). Therefore, anesthesia works not by turning conscious experiences on or off, but rather by interfering with the combination of elementary conscious experiences into a unitary composite conscious experience. In essence, by changing the potential energy barrier landscape in the brain, volatile anesthetics temporarily split the conscious mind into myriad pieces, analogously to how physical severing of the two brain hemispheres generates two separate minds in split-brain patients (Wolman, 2012). The only difference is that the anesthetic action is reversible, whereas the physical severing of the brain is not.

7. Holevo's bound on accessible classical information from quantum measurements

The phenomenal nature of conscious experiences is incommunicable as established by Locke's inverted qualia thought experiment [for a detailed discussion see Georgiev (2017, 2020)]. This means that our introspective access to our own feelings and conscious experiences is fundamentally different from a scientific "observation" whose outcomes can be communicated to others in the form of classical bits of information. In fact, a consistency argument based on indistinguishability of non-orthogonal quantum states also establishes that conscious experiences cannot have the status of observations: if in reductive quantum theories of mind non-orthogonal quantum states comprise different conscious experiences, then we should not be able to report what exactly it is to be in one of the states instead of the other, or which of two non-orthogonal states we have been in, otherwise external observers would have been able to use our reports to distinguish non-orthogonal quantum brain states, i.e. a well-known no-go theorem by Busch (1997) would have been violated.

The incommunicability of consciousness has troubled philosophers for centuries. Whereas we cannot express what the phenomenal nature of qualia is (Nagel, 1974, 1987; Chalmers, 1995), Wittgenstein has argued that we can express some of our feelings in words such as "pain," "anger," or "love," which we all understand (Wittgenstein, 2009; Tang, 2014; Baker, 1998). Quantum physics provides a valuable insight into why we can say something meaningful about our consciousness, but not all there is about it. As we have already elaborated in some detail, the quantum information comprising the quantum state of a quantum physical system is unobservable and cannot be fully converted into classical information. However, Alexander Holevo has been able to show that each quantum system can carry a certain amount of accessible classical information, which does not exceed Holevo's bound (Holevo, 1973, 1998)

$$\chi = S\Big(\sum_k p_k \widehat{\rho}_k\Big) - \sum_k p_k S(\widehat{\rho}_k) \tag{14}$$

where $\{\widehat{\rho}_1, \widehat{\rho}_2, \ldots, \widehat{\rho}_k\}$ is a set of quantum states (described by their *density matrix operators*, cf. (Belinfante, 1980; Hughston et al., 1993; de Gosson, 2018)) that are drawn from the probability distribution $\{p_1, p_2, \ldots, p_k\}$, and $S(\widehat{\rho})$ is the *von Neumann entropy* (von Neumann, 1955; Ohya and Volovich, 2011) of the density matrix $\widehat{\rho}$ measured in bits

$$S(\widehat{\rho}) = -\sum_j \lambda_j \log_2 \lambda_j \tag{15}$$

with λ_j denoting the eigenvalues of the density matrix operator $\widehat{\rho}$. Noteworthy, the von Neumann entropy is a concave functional on the space of density matrices, $S(\widehat{\rho}) \geq 0$. Holevo's accessible information is maximal when: (i) the quantum states $\widehat{\rho}_k$ are pure, that is $\widehat{\rho}_k = |\psi_k\rangle\langle\psi_k|$, since they have zero von Neumann entropy $S(\widehat{\rho}_k) = 0$ leading to

$$-\sum_k p_k S(\widehat{\rho}_k) = 0 \tag{16}$$

(ii) the quantum states $\widehat{\rho}_k$ are orthogonal, $\langle\psi_k|\psi_{k'}\rangle = 0$ for $k \neq k'$ and $\langle\psi_k|\psi_{k'}\rangle = 1$ for $k = k'$, and (iii) the probabilities p_k in the probability distribution are equal. A composite quantum system consisting of n qubits evolves in a Hilbert space with 2^n dimensions. This provides 2^n orthogonal quantum basis states $\widehat{\rho}_k$ available for encoding of classical information. If those 2^n states $\widehat{\rho}_k$ are equiprobable, we get

$$\sum_k p_k \widehat{\rho}_k = \frac{1}{2^n}\begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} \tag{17}$$

with von Neumann entropy

$$S\left(\sum_k p_k \widehat{\rho}_k\right) = -\sum_{k=1}^{2^n} \frac{1}{2^n}\log_2\left(\frac{1}{2^n}\right) = n \tag{18}$$

Combining Eqs. (16) and (18) together implies that for a quantum system of n qubits the maximal value of Holevo's bound is $\chi = n$ bits. In other words, a composite quantum system that contains n qubits can carry up to n bits of accessible classical information, which can be extracted through measurement by an external observer (Holevo, 1973, 1998).

Quantum physics allows orthogonal quantum states to be distinguished even though the same cannot be done unambiguously for non-orthogonal quantum states. Therefore, we may be able to communicate something meaningful in the form of words (bits of classical information) about those of our conscious experiences that correspond to orthogonal quantum brain states (Georgiev, 2020). If consciousness is comprised of quantum information, it will not be completely inaccessible for others, but rather it will have an accessible part which does not exceed the classical bits of information allowed by Holevo's theorem.

Returning back to Wittgenstein's example, we are able to conclude that we do not really communicate the phenomenal qualia of "pain," "anger," or "love," but rather describe distinguishable classical situations under which we expect other humans to consciously experience feelings that are qualitatively similar to ours. For example, one way to explain what the "pain" is could be to note that it is the subjective feeling that we experience when we hit our finger with a hammer. Such an explanation will work for all people who are capable of experiencing pain, but will fail for people with syringomyelia who are unable to feel pain in their extremities due to a cyst that damages their spinal cord (Klekamp and Samii, 2002). Thus, consciousness is not directly observable or directly accessible. We are able to say some meaningful facts about our conscious experiences, but not everything there is about these experiences (Georgiev, 2017, 2020). Holevo's theorem links the orthogonality of quantum states in Hilbert space with the possibility of a partially accessible consciousness by others. Conscious experiences can be private in regard to their phenomenal content (qualia) insofar we can communicate as a string of bits of classical information only the distinguishable physical circumstances for their occurrence. The latter is sufficient to differentiate between conscious experiences with perceptibly distinct phenomenal content and allows us to label these experiences with words such as "pain," "anger," or "love."

Introspectively, we do not perceive ourselves as being built of atoms, molecules or neurons. When we decide to close our eyes or to move one of our limbs, we do not have any idea which neuron in our brain is firing to deliver the appropriate electric signal to our muscles. Yet, if we undergo open skull neurosurgery, our brain can be observed and its electric activity recorded. Thus, the brain may appear to be what the conscious mind looks like from a third-person, objective perspective. But according to quantum information theory this cannot be exactly right. If consciousness comprises the quantum information in the existing quantum brain state, then it cannot be observed. Instead, upon measurement of some quantum observable of the brain, the quantum state has to choose a possible quantum outcome among the possible eigenvalues of the observable. Thus, the observable brain is the classical record of observable eigenvalues of past mind choices (decisions). The irreversibility of mind choices ensures that the observable brain is an objective construct for all possible observers. Because the anatomical brain is accessible classical information, it can be observed, shared, communicated, copied and analyzed by multiple observers. The observability of the brain supports objectivity in neuroscience as it grants multiple scientists with simultaneous access to multiple identical copies of classical information about the same brain, which can then be analyzed independently.

8. Concluding remarks

Our conscious minds exist in the physical universe where they appear to be causally potent agents capable of controlling our behavior and transforming the surrounding world (Yablo, 1992; Crane and Brewer, 1995; Jackson, 1996). Therefore, if we are to have a scientific theory of consciousness, conscious experiences should be represented in physical equations and need to be governed by physical laws (Georgiev, 2013, 2017). In a classical world, all physical quantities are observable and communicable. This severely restrains the scope of classical physical theories because an unobservable and incommunicable consciousness cannot be reduced to anything already present in the physical equations. Instead consciousness needs to somehow emerge as a functional product of the observable brain, which will unfortunately turn the emergent consciousness into a useless, causally ineffective epiphenomenon overrun by the deterministic laws of classical physics (Georgiev, 2019). In a quantum universe comprised of unobservable and incommunicable quantum information, however, epiphenomenal consciousness is avoidable thanks to quantum indeterminism, and the perplexing inner privacy of consciousness could be seen to originate in the physical properties of quantum information integrated in brain cortical quantum states (Georgiev, 2017, 2020; Melkikh and Khrennikov, 2015; Melkikh, 2019).

In the quantum reductive approach to consciousness, conscious experiences are identified with quantum brain states, which are in some relevant sense private or noncommunicable. When we introspect our quantum conscious states, we are able to report only a certain amount of classical information that does not exceed Holevo's bound. The incommunicable qualia of conscious experiences, which are privately accessed through introspection, then correspond to quantum information that cannot be converted into classical information. This incommunicable quantum information is inaccessible to external observers. Thus, introspection *is not* equivalent to quantum measurement. We continuously experience the contents of our conscious minds, which means that the introspective access to our inner mental world, provided through identity relation between consciousness and quantum information contained in the quantum brain state Ψ, is continuous and not discrete. The unitary quantum evolution of the quantum brain state Ψ, which among other things also leads to entanglement of different brain subcomponents, describes changes in unobservable conscious experiences and their binding or composition. The quantum measurements of the brain are discrete events performed by effector organs such as muscles or glands, which react to neuronal electric impulses outputted by efferent axon terminals. The glial cells, which nourish the neurons, also perform quantum measurements upon brain neurons for the purposes of maintaining proper homeostasis of brain electrolytes or other chemicals. The measurement of quantum brain observables by glial cells, effector organs or physical devices leads to decoherence of the quantum brain state Ψ and extracts accessible classical bits of information from which is constructed the "observable brain." Thus, quantum information theory addresses the mind–brain problem by utilizing the dichotomy between quantum state vectors and quantum observables.

The quantum physical laws, expressed in the Schrödinger equation and the Born rule, introduce a paradigm shift in consciousness research by making all physical statements about the mind or the brain subject to mathematical precision. General statements valid for all physically admissible Hamiltonians, which govern the dynamics of the quantum system, are subject to quantum no-go theorems. This can resolve philosophical problems only by considering the physical properties of quantum information without the need of explicitly solving any equations. Specific statements valid for a concrete biomolecular Hamiltonian, however, require quantum chemical methods for solving numerically the many-body Schrödinger equation. Currently available supercomputers allow the derivation and experimental testing of quantum predictions for physical systems consisting of several thousand atoms. Future developments of faster supercomputers and better techniques for numerically solving the Schrödinger equation will enable even tighter integration of quantum physics in consciousness research.

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Declaration of competing interest

The author declares that he has no conflict of interest.

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