Some Macroscopic Applications of Georgiev's Quantum Information Model

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ABSTRACT

The goal of this paper is to review a recently published model of quantum neuroscience in which it is proposed that consciousness and free will can be explained by directly identifying consciousness with quantum entanglement and directly identifying free will with the objective reduction of a quantum entangled system. In the second part of the paper, the model is applied to two examples of neurological processing which are difficult to explain in the context of a model that denies the existence of free will, namely task set selection and selective attention. In both cases, it is shown that, if the two possible outcomes of a process are modeled as a single quantum entangled network, the selection of one outcome or the other can be explained by the free will that is inherent in the objective reduction of the network.

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Introduction

The notion of volition, or free will, has intrigued philosophers and psychologists for centuries. However, in recent decades there has been mounting evidence to suggest that the notion of free will is incompatible with the deterministic laws of classical physics. As a result, several researchers have proposed that, in order to account for free will without sacrificing scientific rigour, a model of brain function based on the probabilistic rules of quantum physics is needed. One of the most important obstacles that these researchers have had to deal with is the question of how best to apply quantum principles coherently on a macroscopic level. The goal of this paper is to contribute to this line of research by reviewing a recently proposed model of quantum consciousness (Georgiev, 2018) that provides a unique approach to this complex problem. In the second part of the paper, Georgiev's model will be applied to two problems in the field of neurological processing that are closely tied to the question of free will, namely task set selection and selective attention.

Georgiev's Quantum Information Model

Georgiev begins his presentation by informally defining "consciousness" as "the subjective, first-person point of view of our mental states, experiences or feelings" (Georgiev 2018), and "free will" as "the capacity of agents to choose a course of action from among various future possibilities" (Georgiev 2018). He then goes on to present his quantum information model, the principles and formalism of which are fairly consistent with the well-known Copenhagen interpretation of quantum mechanics. With respect to the complex issue of defining consciousness in quantum terms, he proposes a unique solution, which consists of directly identifying consciousness with the state vector representing the wave function of a quantum entangled system:

> To each individual conscious mind corresponds a single non-factorizable (quantum entangled) state vector $|\Psi'\rangle$ that resides in a subspace of the Hilbert space of the universe $\mathcal{H}_{U}$, and to each non-factorizable state vector corresponds a single mind (Georgiev, 2018).

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An obvious potential objection to this axiom is that it is far too inclusive, in that it predicts that a structure as simple as a single pair of entangled subatomic particles corresponds to a conscious mind. In addition, the axiom predicts that a conscious mind can be created not only in the brain, but also in other parts of the body, and even in inanimate objects. Georgiev addresses this issue by considering entanglement from a quantitative perspective:

For inanimate objects such as rocks, the quantum information theory of consciousness will predict that the growth of entangled clusters and subsequent objective reductions will occur in a stochastic, disorganized and asynchronous fashion. Thus, the rock will be unconscious because it is a *collection of minds* that stochastically pop in and out of existence. The physical properties of the rock will be the statistical average of a zillion [*sic*] stochastic quantum processes (Georgiev, 2018).

In other words, an elementary form of consciousness is indeed created in every quantum entangled structure, however only neurons possess the properties needed to produce consciousness at a non-trivial level.

In similar fashion, Georgiev defines the concept of free will by directly identifying it with a fundamental component of his model, namely objective reduction of the wave function. Specifically, he begins by defining objective reduction using the following axiom:

For composite non-factorizable (quantum entangled) quantum systems with a state vector $|\Psi'\rangle$ there is an energy threshold $\mathcal{E}$ at which objective reduction and disentanglement of the individual subsystems could occur [...], with probability for the actualized outcome given by the Born rule [...] (Georgiev, 2018).

He then goes on to show that, because it is impossible to predict the outcome of the process of objective reduction, the process is in fact "a physical manifestation of the inherent free will enacted by the quantum physical systems" (Georgiev, 2018). As in the case of his definition of consciousness, Georgiev argues that the extremely wide scope of his definition of free will is not problematic because only neurons possess the characteristics needed to allow free will to manifest itself at a non-trivial level.

In order to show how this model of consciousness and free will can manifest itself at the cellular level, Georgiev adopts an idea originally proposed by Beck and Eccles (Eccles, 1986; Beck and Eccles, 1992; Beck, 2008), according to which quantum-level processes can play a role in the regulation of exocytosis. Specifically, Georgiev shows that the neurons in the human cortex have, on average, approximately 7000 synapses, and that, when an electrical impulse arrives at a nerve terminal, the probability of exocytosis in a given synapse is approximately 0.35. He goes on to argue that, given the enormous structural and functional complexity of the brain, the regulation of exocytosis could not possibly be stochastic, and that some sort of stable regulator must therefore be present. Georgiev presents a detailed analysis of the molecular structure of the synapse, and concludes that the best candidate for the regulation of exocytosis is a group of three proteins collectively referred to as "Soluble NSF Attachment Receptor" ("SNARE") proteins. Specifically, he shows that the conformation of these proteins at the neural synapse allows for the creation of a quantum quasiparticle called a Davydov soliton. He goes on to propose a model based on quantum tunneling of this soliton across a potential energy barrier, and shows that the model is able to reproduce the experimentally determined exocytosis probability of 0.35.

The model outlined thus far shows how quantum mechanics can play a role at the level of communication between neurons. However, even at this level, the elementary form of consciousness and free will that is manifested is negligible. What is needed is a mechanism that explains how this model can apply coherently to large networks of neurons. Georgiev does present theoretical evidence to show that quantum entanglement can be non-local, but few details are provided regarding the precise mechanism involved. A possible solution to this problem can be found by comparing Georgiev's model to that of Flohr (2000; 2006). The primary goal of Flohr's research is to show how consciousness can be impaired by various anaesthetics and hallucinogens. Flohr provides extensive evidence to show that impairment of consciousness always involves the N-methyl-D-aspartate (NMDA) receptor, a glutamate receptor which has been shown to play a pivotal role in exocytosis (Furukawa *et al.*, 2005; Li and Tsien, 2009; Zito and Scheuss, 2009). The breadth of the evidence that Flohr presents in support of his model allows him to conclude that "[a] minimum activation of the cortical NMDA system is a necessary condition for the mechanisms underlying consciousness" (Flohr, 2000).

In order to provide a more precise description of the relationship between the functioning of the NMDA receptor and consciousness, Flohr makes reference to the well-known "neurons that fire-together, wire together" model proposed by Hebb (1949; 1959). Specifically, Flohr shows that the NMDA receptor is an example of a "Hebbian coincidence detector". According to Hebb's model, when a molecule (such as NMDA) detects coincident presynaptic and postsynaptic activity, the relationship between the two neurons is strengthened. This process can be repeated over and over, resulting in the creation of neural networks, which Hebb refers to as "cell assemblies". Hebb also notes that this type of assembly is at the heart of the brain's ability to create a mental representation of a stimulus: "In short, the assembly activity is the simplest case of an *image* or an *idea*: a representative process" (Hebb, 1959). Flohr takes this idea a step further, proposing that consciousness corresponds to the "embedding" of a mental representation into a larger, more complex neural assembly:

The NMDA synapse appears to be ideally suited to tie together and integrate widely distributed activities and to organize large-scale neuronal assemblies. Such assemblies detect coincident lower-level neuronal events in segregated specialized cortical areas, and bind them into a coherent percept that represents a higher level of correlation between *internal* events. It instantiates self-reflexive representations of the system itself and of its current state. (Flohr, 2000)

A comparison of Georgiev's model with that of Flohr reveals some interesting properties. First, there is considerable recent evidence (Gu and Huganir, 2016; Cheng *et al*., 2013; Hussain *et al*., 2016) that SNARE proteins play an important role in the functioning of the NMDA receptor. This clearly lends support to the idea that there is a relationship between Flohr's model of Hebbian neural networks and Georgiev's model of quantum entanglement. More precisely, it could quite plausibly be argued that Flohr's wide-scale neural networks provide the mechanism needed for the creation of Georgiev's wide-scale quantum entangled structures. Second, with respect to the complex "embedded" neural networks that are central to Flohr's model of consciousness, the subjective aspects of consciousness could be explained using Georgiev's model of objective reduction.

Task Set Selection

The information provided in the previous section shows how Georgiev's quantum information model could apply to wide-scale neural networks. In this section, the model will be applied to a problem that has proven difficult to explain in terms of classical physics, namely motor task selection. The starting point for this section will be the model outlined by Haggard (2008). This model was chosen specifically because Haggard is well aware of the difficulties associated with accounting for free will using classical physics. He, therefore, explicitly excludes the possibility that free will can play a role in task selection.

According to Haggard's model, the brain is constantly receiving stimuli from various sources, and some of these stimuli demand a response in the form of a physical movement. The resulting actions can be subdivided into two basic categories, which Haggard refers to as "stimulus-driven" actions and "voluntary" actions. As the name suggests, stimulus-driven actions occur in situations where there is a clearly identifiable stimulus that unambiguously demands a specific response. A typical example is the withdrawal reflex that occurs when a specific part of the body receives a painful stimulus. There is general agreement among researchers that stimuli of this type are transmitted from sensory neurons to the relevant motor neurons with little or no intermediate processing. In contrast, voluntary actions are performed in situations where the stimulus is unfamiliar, ambiguous or underspecified. In such situations, more complex processing is required. Haggard provides extensive evidence to show that the preliminary processing occurs primarily in the pre-supplementary motor area (pre-SMA). The role of this area appears to be the retrieval of information needed to produce an appropriate motor action in response to the stimulus. Specifically, the pre-SMA receives information from two primary sources. First, a subcortical "loop" between the pre-SMA and the basal ganglia (BG) provides information regarding the potential reward value of a given task set. Second, the prefrontal cortex (PFC) uses the reward value information to make three decisions. The first decision is what Haggard refers to as a "whether" decision. In short, the PFC decides whether or not it is worthwhile to respond to the stimulus. The second decision, referred to as a "what" decision, involves

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retrieving potential task sets from long-term memory, and using the potential reward value information to choose the "optimal" task set. The third decision is what Haggard refers to as a "late whether decision". This involves a "final check" of the motor action corresponding to the chosen task set, and a decision to either transmit the action to the motor cortex or cancel the action completely. Haggard mentions that this stage of the process corresponds closely to the "conscious veto" that is an integral component of the well-known "free won't" model of volition developed by Benjamin Libet (see Libet 1999 for an overview).

As previously mentioned, Haggard's model assumes that free will plays no role in decision making. This clearly avoids the difficult problem of accounting for mind-brain interaction, however it also places important restrictions on the model. Specifically, there is no place in the model for subjectivity of any kind, and all of the decision making that Haggard proposes must be explained in terms of neurological processing. This raises a potential problem in terms of learning. Specifically, the model predicts that the PFC can do nothing more than determine, based on an assessment of potential reward value information, which task set would be the "optimal" response to a given stimulus. It is true that, after the action corresponding to the chosen task set is performed, the brain has the ability to analyze the effectiveness of the action, and use this information to "update" its repertoire of responses, however this represents an extremely slow learning process. In order to account the fact that the brain's ability to learn new responses to stimuli is much faster than what such an "updating" model would predict, Haggard proposes that there must be a mechanism which allows the brain to engage in what he calls "exploratory" behaviour. In other words, the brain must have the ability to choose responses other than those that are objectively determined to be "optimal". However, given the constraints of the model, Haggard can only conclude that such choices are the result of "random behavioural noise" (Haggard, 2008).

Haggard's contention that the choice of a "non-optimal" task set must be random suggests that Georgiev's model could be used to introduce free will into the selection process. Specifically, if the three instances of decision making in Haggard's model were modeled as quantum entangled neural networks, the free will that is inherent in Georgiev's model of objective reduction could account for the fact that a "non-optimal" response, although statistically less likely than the "optimal" response, could be chosen in certain situations.

Selective Attention

Much like consciousness and free will, attention is a phenomenon that has proven very difficult to define in scientific terms. According to William James, whose *Principles of Psychology* is considered a cornerstone of modern psychology, attention is "the taking possession by the mind, in clear and vivid form, of one out of what may seem several simultaneously possible objects or trains of thought. ...It implies withdrawal from some things in order to deal effectively with others" (James 1890: 403). From this perspective, attention could be defined simply as the allocation of neural processing resources to a particular stimulus, at the expense of other stimuli. However, a review of the recent literature in this area shows that the concept of attention is more complicated than what such a simple definition would suggest. Of particular importance in this regard is the distinction, made by several authors (Ciaramelli *et al*., 2010; Katsuki and Constantinidis, 2014), between "bottom-up" and "top-down" attention. Bottom-up attention is based on the stimulus itself. A bright light or a loud noise, for example, will tend to attract the attention of the brain more than a stimulus which lacks such salience. Top-down attention (which is often referred to as "selective attention" in the psychological literature) is a much more complex phenomenon. According to Katsuki and Constantinidis (2014), top-down attention refers to "internal guidance of attention based on prior knowledge, willful plans, and current goals". It is interesting to note that James (1890) was very much aware of the importance of the top-down aspects of attention. In fact, James believed that the voluntary decision to pay attention to a particular stimulus was at the heart of the concept of free will: "[A]ttention with effort is all that any case of volition implies. The essential achievement of the will [...] is to attend to a difficult object and hold it fast before the mind. [...] Effort of attention is thus the essential phenomenon of will" (James, 1890). In the context of the model presented here, the distinction between bottom-up and top-down attention is of great importance, because bottom-up attention can easily be explained within the context of a processing model based on classical physics, whereas top-down attention, which clearly involves free will, requires a quantum-based model.

In the previous section, it was shown that there are certain aspects of task-set selection that are difficult to explain in the context of a model based on classical physics which excludes free will. Similarly, there are examples in the literature of processes involving selective attention that are difficult to explain without a quantum-based model that can account for free will. A prime example can be found in the research of psychiatrist Jeffrey Schwartz (Schwartz and Begley, 2002) on the treatment of Obsessive-Compulsive Disorder (OCD). Schwartz's research shows that the difficulties that OCD patients experience are due primarily to hyperactivity between two areas of the cortex, namely the Orbital Frontal Cortex (OFC) and the Anterior Cingulate Gyrus (ACG), and the striatum, which is part of the BG system. Schwartz refers to these pathways as the "OCD circuit". As a result of this hyperactivity, patients report being overwhelmed by the feeling that something is "wrong" or "amiss" and needs to be fixed. Schwartz's treatment method involves helping patients to resist the urge to perform the actions that the OCD circuit is compelling them to perform.

The OCD patient is faced with two competing systems of brain circuitry. One underlies the passively experienced, pathological intrusions into consciousness. The other encodes information like the fact that the intrusions originate in faulty basal ganglia circuits. At first the pathological circuitry dominates, so the OCD patient succumbs to the insistent obsessions and carries out the compulsions. With practice, however, the conscious choice to exert effort to resist the pathological messages, and attend instead to the healthy ones, activates functional circuitry. Over the course of several weeks, that regular activation produces systematic changes in the very neural systems that generate those pathological messages – namely, a quieting of the OCD circuit (Schwartz and Begley, 2002).

The fact that Schwartz's treatment method involves using a "conscious choice to exert effort" strongly suggests that free will is involved. Simply put, Schwartz's patients are receiving very powerful, insistent messages from their brain, and they are attempting to do the opposite of what the messages are telling them. It is interesting to note that, unlike most researchers in this field, Schwartz is very much aware of the difficulties associated with accounting for free will in a model based on classical physics. As a result, Schwartz's treatment method makes reference to certain principles of quantum mechanics (although the specific model adopted by Schwartz is quite different from the model presented here). From the perspective of Georgiev's model, the "two competing systems of brain circuitry" described by Schwartz could be viewed as a large quantum-entangled system in which the "pathological messages" have a much higher probability of being realized than the "healthy messages". Schwartz's treatment method could then be viewed as helping patients to use free will to increase the probability associated with the realization of the "healthy messages".

Another example of selective attention that appears to require free will is related to the identification by several researchers (Raichle *et al*., 2001; Garrison *et al*., 2015; Mak *et al*., 2017) of a group of neural networks collectively referred to as the brain's "default mode network" (DMN). The regions that are most commonly mentioned as being part of this network are the medial PFC, the posterior cingulate cortex and the angular gyrus. As the name suggests, this network is believed to be responsible for the functioning of the brain in situations where no specific cognitive task is being performed. According to Raichle *et al*., (2001), an important function of the DMN is to "scan" the environment for potential dangers. The basic idea is that, when no specific cognitive task is being performed, the brain will tend to switch its focus relatively quickly from one stimulus to the next, paying minimal attention to each stimulus that it receives. However, if a particular stimulus is determined to be particularly important or indicative of potential danger, the brain will divert processing resources away from the DMN and towards the processing of the stimulus in question.

An example of a process that appears to involve the use of selective attention to "override" the DMN can be found in the recent literature on mindfulness meditation. Mindfulness is defined by Kabat-Zinn (2003) as "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment". Although there are several different techniques associated with mindfulness meditation, one of the most common, especially for novice meditators, involves focusing attention on a single stimulus, often the sensations associated with breathing.

Several recent studies (Brefczynski-Lewis *et al*., 2007; Brewer *et al*., 2011; Moore *et al*., 2012) have shown that mindfulness meditation improves the ability to focus on a single stimulus and ignore distracting stimuli. Specifically, these studies provide brain imaging data which show that, during mindfulness meditation, novice meditators show relatively little activity in the areas of the brain that are related to the performance of the task at hand (i.e. the allocation of attention to one's breathing). In addition, they show little or no reduction in the level of activity of the DMN when compared to a resting state. The brain imaging evidence is corroborated by anecdotal data from the novice meditators, who report that their meditation is frequently interrupted by "mind-wandering" or "mental chatter", which is characteristic of DMN activity. The studies cited above also show that, after several hours of practice, meditators gradually achieve a reduction in DMN activity, and a corresponding improvement in the focusing of attention on the task at hand.

As in the case of Schwartz's "OCD circuit", the DMN clearly represents a strong disposition for the brain to behave in a particular way. In addition, the fact that many hours of conscious effort is required to "override" this disposition strongly suggests that free is involved. From the perspective of Georgiev's model, the effects of mindfulness meditation could be explained by postulating that the DMN and the efforts of meditators to focus on a single stimulus represent a large quantum entangled network in which the effects of the DMN initially have a much higher probability of being realized. Over the course of many hours of conscious effort, free will can be used to gradually increase the probabilities associated with the efforts of meditators to focus their attention.

Summary and Outlook

The goal of this paper was to outline Georgiev's (2018) quantum information model, and to consider applications of the model to two examples of neurological processing that are difficult to explain in the context of a model based on classical physics. The key points of the paper are summarized below:

- According to Georgiev's model, consciousness is identified with quantum entanglement, and free will is identified with objective reduction of an entangled system.

- At the cellular level, Georgiev's model manifests itself by regulating exocytosis.

- At the level of neural networks, Flohr's model of wide-scale Hebbian networks provides a plausible mechanism for the creation of the wide-scale quantum entangled structures that are a necessary component of Georgiev's model.

- Haggard's model of task-set selection shows that the choice of an "optimal" task set can be explained by a model based on classical physics that makes no reference to free will. However, the choice of a "non-optimal" task set requires a quantum-based model. From the perspective of Georgiev's model, the two choices could be modeled as a large quantum entangled network. Because of the free will that is inherent in Georgiev's model of objective reduction, the "non-optimal" choice, although statistically less likely, is nevertheless possible.

- With respect to selective attention, evidence from research on OCD treatment and mindfulness meditation suggests that, in situations where the brain is strongly predisposed to behave in a particular way, conscious effort can nevertheless be used to gradually "override" the predisposition. The evidence strongly suggests that free will must be involved. As in the case of task-set selection, Georgiev's model allows for the two possible outcomes to be represented as a quantum entangled network in which the efforts to "override" the predisposition gradually become more frequent.

In conclusion, while there are many details that require further research, it is hoped that the model and the applications presented here will prove useful to researchers as they continue to work towards a better understanding of the relationship between quantum neuroscience and free will.

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