Thinking as a quantum phenomenon

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Thinking as a quantum phenomenon

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ABSTRACT

In this study, a model is constructed in which the formation of new synaptic contacts and the tuning of synaptic weights are mediated by quantum nonlocal interactions. The interaction between biologically important molecules in the brain can be the basis of the quantum metalanguage, which controls the behavior of humans and animals. The dynamics of biologically important molecules must include their topological properties. Thus the work of the brain can only be consistently described using quantum mechanics.

1. Introduction

The act of thinking is one of the most heavily researched phenomena in science, but despite this, the mechanisms of thinking remain largely unclear. One of the key unresolved issues is the unclear relationship between thinking and the brain. This issue has been discussed repeatedly since the very emergence of science. In particular, in recent decades, a number of authors have advanced the assumptions regarding the role of quantum mechanics in brain function and thinking. Another important issue is understanding the origin of new knowledge. For example, in Melkikh, 2014a; Melkikh et al., 2018, the existence of innate behavioral programs based on quantum processes has been proposed as a mechanism of this process. Thus, the processes of thinking and the work of the brain can, to a greater or lesser degree, have a quantum nature.

We can distinguish three significant motivations for the application of quantum mechanics to the processes of thinking and brain function.

One of the first motivations is the set of ideas of Penrose and Hameroff (Penrose, 1989; Hameroff, 1994, 2003, Hameroff, Penrose, 2014), who suggested that mental processes are associated with the collapse of the wave function, which is caused by the effects of gravity. In this case, **non-computability** plays an important role in the processes of thinking. According to the author (Penrose, 1994), the ability to understand cannot be formalized within a particular set of rules. The author comes to the conclusion that for the establishment of mathematical truth, mathematicians do not apply justified algorithms. According to the author (Penrose, 1994), this applies not only to mathematics but also to thinking in general. At present, this trend continues to develop (see, for example, Craddock et al., 2015, 2017).

Another important application of quantum mechanics to cognitive sciences is **decision making**. This field is actively developing and includes many researchers (see, for example, Bagarello et al., 2017; Basieva et al., 2017; Khrennikov, 1999, 2010a, 2010b, 2011, Aerts et al., 2011, 2013, Dzhafarov and Kujala (2012); Pothos and Busemeyer, 2013). The main motivation in this field is to solve, with the help of quantum mechanics, paradoxes in decision-making. Such paradoxes, for example, include the Elsberg paradox, a violation of the sure-thing principle, among others. In the authors' opinion, it is quantum mechanics that makes it possible to explain the decision making in situations that classical probability theory cannot explain. The most important property of quantum probabilities is that in addition to the usual classical probabilities, they contain interference terms related to the wave character of quantum particles.

The third motivation can be attributed to the fact that the brain itself, on the basis of which thinking is realized, functions as a fundamentally quantum system. Studies (Melkikh, 2014b; Melkikh and Meijer, 2018) have shown that neural behavior is contradictory at the molecular level. This is reflected in the fact that the accuracy of protein-ligand and protein-protein biochemical reactions, protein and DNA (RNA) folding, cannot be explained by the presence of short-range potentials between biologically important molecules. In this case, the entangled (in the classical sense) and inoperable states of macromolecules should be realized with an overwhelming probability. This phenomenon, in particular, will lead to inefficient substance transport both inside neurons and through neural membranes. Taken together (formulated by the authors as a **generalized Levinthal's paradox**), these findings requires a revision to our understanding of the mechanisms of the cellular function at the molecular level. To solve the paradox, the authors propose a quantum model of intermolecular interactions. The most significant point of this model is the long-range

interaction, which ensures the efficient operation of intracellular molecular machines. In this instance, the motivation for using quantum mechanics is based on the fact that classical mechanics cannot *in principle* provide such an interaction.

This paper is devoted to the development of ideas regarding the quantum basis of cell function (including neurons), previously expressed in the papers (Melkikh, 2014a, b, Melkikh and Meijer, 2018). In particular, the topological aspect of quantum effects in neural function will be considered, providing a basis for thinking to be understood.

2. Quantum effects in neural function. Does non-computability impact the brain's work?

Before discussion quantum effects in the brain, consider the definitions of some of the most important concepts.

Thinking is the most common property of a human to reflect the surrounding reality. Thinking is closely related to the work of the brain, but this connection is largely unclear. At present, forms of thinking that are not related to the work of the brain are not known, but on the other hand, it is not possible to localize in the brain the molecular structure with which thinking is connected directly. The distinctive feature of thinking is the property to receive knowledge about such objects, properties and relations of the surrounding world, which cannot be directly perceived.

Knowledge is an image of the surrounding reality, expressed in the form of concepts. In a narrower sense, knowledge is information about the surrounding world, which may be more or less true. However, the mechanism for acquiring new knowledge remains largely unclear.

Part of the thinking process is understanding. The most important property of understanding is that after understanding the actions of a human (the intellectual system) become more adequate than before. Understanding is closely related to recognition of the environmental. The recognition procedure in the most general form includes a comparison of the image obtained by the receptors with a certain standard. As a result, there may be two possible options: either the image coincides with the standard (corresponds to it) or not.

As noted above, the application of quantum mechanics to thinking can also be justified by the fact that the brain itself, on the basis of which thought is realized, functions as a fundamentally quantum system. One of the main problems of molecular biology is protein folding. The problem (Levinthal's paradox) is that a protein that is synthesized as a linear molecule must somehow find its native conformation. However, for long proteins, the total number of possible conformations is exponentially large, and a simple enumeration of the variants cannot be performed within relevant cellular timescales.

According to (Melkikh, 2014b; Melkikh and Meijer, 2018), problems arise during the folding of macromolecules because energy-equivalent states will always occur; thus, these states will be realized with equal probability. For example, for a one- or two-component system, the presence of such states (folding forks) is quite easy to show (Fig. 1) (see, also Melkikh, 2013).

Due to these equal configurations, the energy landscape is fragmented, and the probability of reaching a native state during folding is small. In this case, the entangled (in the classical sense) and inoperable states of macromolecules should be realized with an overwhelming probability. This situation, in particular, would lead to inefficient transport of substances both inside neurons and across neural membranes. Taken together (formulated by the authors as a generalized Levinthal's paradox) this issue requires a revision to our understanding of the mechanisms of the cellular function at the molecular level.

To solve the generalized Levinthal's paradox, a quantum model of the interactions of biologically important molecules has been constructed and published (Melkikh, 2014a; Melkikh and Meijer, 2018). According to this model, we can write
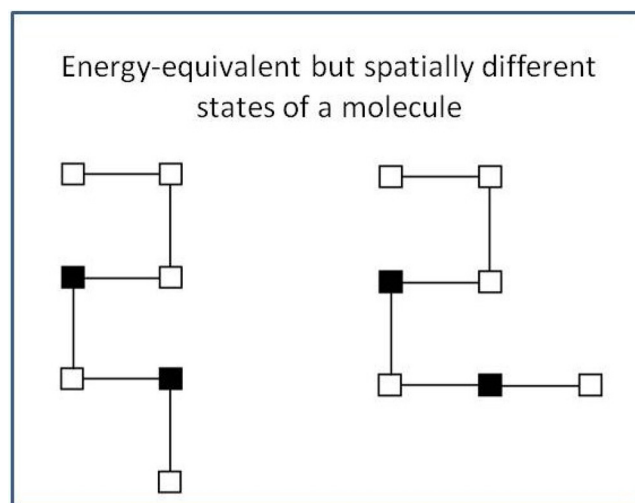

Fig. 1. Energy-equivalent but spatially different states of a molecule.

$$i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi + \varphi\psi, \tag{1}$$

$$\frac{\partial\varphi}{\partial t} = g(\varphi, \psi). \tag{2}$$

Here ψ - is the wave function, $\hat{H} = -\frac{\hbar^2}{2m}\Delta + U$ - is the Hamiltonian, which includes the kinetic and potential energy operators, respectively.

The first equation is the Schrödinger equation for a particle; in addition to the usual Hamiltonian, this equation also contains a potential related to the collective interaction of particles.

The second equation describes the dynamics of this type of many-particle potential. This particular potential organizes collective effects so that protein folding and other processes of interaction between biologically-important molecules occur with the funnel-like landscape.

The most significant aspects of this model are the long-range interaction and the collective character of the operator φ. The latter implies that the superposition principle does not hold for φ:

$$\varphi_\Sigma \neq \sum_i \varphi_i$$

The non-locality exhibited by this model brings it together with Bohm's theory. This connection makes it promising for modeling biological systems, particularly morphogenesis (Melkikh and Khrennikov, 2018).

Penrose and Hameroff presented a hypothesis regarding the important role of microtubule quantum states in neural function and consciousness. It was suggested that tubulin conformation can transfer and process information within the cell. One of the basic assumptions of the model is the role of gravity in the process of wave function collapse. In particular, according to Penrose, the shift of masses makes the superposition of quantum states unstable. In the Penrose model, the elementary OR event can be viewed as an act of measurement or as a proto-consciousness. Moreover, non-computability plays an important role. According to the author, the ability to understand cannot be formalized within a particular set of rules. The author comes to the conclusion that to establish the truth, known algorithms cannot be applied. The reason for this, according to the author, is Gödel's incompleteness theorem, the consequence of which is that conscious thinking contains a non-computable component.

However, the problems of non-computability and unprovability are not directly related to the neural function or thinking. Obviously, non-computability and unprovability occur only within a certain language (an axiomatically closed mathematical system). There is no reason to assert that the language we use in the process of thinking is closed and unchanged. It is quite possible to imagine that we are only aware of a
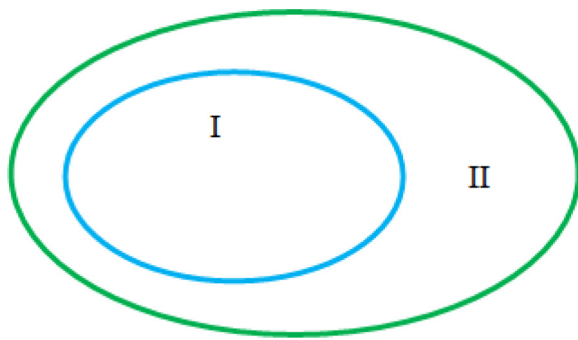
Fig. 2. The set that we are conscious of during thinking (I) and the set that includes unconscious processes (II).

part of the language and that the rest remains unconscious. For example, Melkikh et al. (2018) used a concept of the quantum metalanguage, which control our language. This proposal can completely abolish the problem of non-computability because through it our language becomes an open system. Other issues arise, however, as within the framework of the quantum metalanguage, there are other unprovable statements.

Fig. 2 shows the set that we are conscious of during thinking (set I) and the set that includes unconscious processes (set II). What is unprovable within the framework of I can very well be proved in the framework of II. It is clear that the work of the brain involves many processes that we are not conscious of. It is certain that we are not conscious of the opening and closing of ion channels, work of neuroreceptors, spread of nerve impulses, transport of neurotransmitters, etc. However, it is these processes that are closely related to thinking. This can be proved by the fact that disturbances in all these functions lead to disturbances in thinking (neurodegenerative diseases, etc.). Thus, it cannot be excluded that some thinking processes are not conscious. This does not mean that the most important processes are necessarily unconscious, but only indicates that they exist.

As the Penrose-Hameroff theory is developed further, one can consider, for example, works (Craddock et al., 2015; Cocchi et al., 2017) that evaluate the effects of quantum mechanisms within anesthetic gases and how these effects influence consciousness. Exciton energy transfer is proposed as such a mechanism. Exciton energy transfer is proposed as such a mechanism. For example, one group showed (Craddock et al., 2017), on the basis of experimental data, that anesthesia arises due to a change in the dipole oscillations of the electronic degrees of freedom of aromatic molecules in proteins. Because of the polarization, the frequencies of collective oscillations change. In particular, cytoskeletal microtubules are one of the main regions responsible for binding anesthetic gases. In this case, coherent theories of anesthesia suggest that anesthetics, by interacting with microtubules, alters the shape of the neuron, the growth of dendrites and intra-neuronal transport.

In other works (Cocchi and Minuto (2015); Cocchi et al., 2017), it is noted that heterogeneous populations of neurons and glia are not sufficiently understood at the molecular level. Previously, considerable attention was paid to genes and proteins, but lipids remained in the shadows. The authors pay great attention to linoleic acid. In the authors' opinion, this acid may play a role in breaking the symmetry of neuronal membranes through a mechanism that has similarity to magnetization. In particular, this mechanism manifests itself in long-range ordering near the critical point. According to the authors, this effect can spread to the entire brain.

Experimental data (Cocchi et al., 2017) indicate that a small concentration of these acids correlates with certain diseases of the brain. There is a connection between linoleic acid and the cytoskeleton as well as with G-proteins. In this study, the authors see a connection with the Ising model. The trans- and cis-states of molecules in this sense can be

considered as analogs of two different spin states. Such cis- and trans-states can affect the operation of ion channels, leading to synchronization (or desynchronization) of their operation.

As motivation for this study, besides non-algorithmism, the authors suggest understanding rapid athletic reaction to external stimuli, as well as a quick (non-algorithmic?) solution to problems (insight) that they have not previously met.

The authors proposed a model in which the ions that pass through ion channels are entangled with each other. In this case, fatty acids control this process.

The authors (Cocchi et al., 2017) considered further transfer of information: actin filaments interact with the membrane and transmit signals from the channels further into the cell. With the actin filaments' help, the cytoskeleton can also affect the membrane. G-proteins are used as shuttles between the membrane and actin and tubulin. In this way, according to the authors, the cytoskeleton can influence action potential. We note in this connection that to organize the action potential, the coherent operation of ion channels is not required, and the potential itself can be considered classically.

Other ions and molecules also affect cytoskeletal function. For example, divalent ions such as magnesium and zinc are involved in stabilizing the cytoskeleton (Cocchi et al., 2017), however, calcium destabilizes them. Thus, the cytoskeleton is reorganized in response to the action potential. Neurotransmitters also affect the dynamics of microtubules.

Thus, according to the authors (Cocchi et al., 2017), phase transitions in membrane fatty acids control many events in the cell. Anesthesia prevents the passage of the action potential. Anesthesia prevents the passage of the action potential. Anesthetics satisfy the key-lock paradigm, interacting with the hydrophobic regions of proteins and membranes. In this way, they can attach to the cytoskeleton or proteins in the membrane. Antidepressants act on monoamine transporters. However, as noted above, the use of the key-lock paradigm in relation to complex biologically important molecules is problematic.

According to the current model (Melkikh, 2014b; Melkikh and Meijer, 2018), fatty acids, G-proteins, ion channels, and microtubules can be considered to be part of a single code. This question will be considered below.

In work (Vaziri and Plenio (2010)), it is stated that the tunnel effect plays an important role for the ions in channels. Is such an effect truly significant for ions transported through membranes? As is known, in condensed matter, only protons (because of their low mass) can exhibit quantum effects (tunnel effect) during diffusion. However, in order for the sodium-23 and potassium-40 ions to play a comparable role, the energy barrier should be a corresponding number of times smaller. In this case, the barrier is simply so small that it decreases than kT and can be neglected. This will cause quantum effects to be too small. The opposite case (the large barrier) is also not realized, because in this case, the reactions will proceed very slowly, and the probability of overcoming such a barrier will be notably small and virtually unmeasurable.

Summhammer et al. (2012) also argue that the passage of ions through ion channels should be associated with quantum effects. The authors show that the solution of the Schrödinger equation describes the interaction of one potassium ion with the surrounding dipoles within the framework of the Berneche-Roux model of the bacterial KcsA model channel. The authors showed that depending on the remaining carbonyl-derived potentials, alkali ions can become highly delocalized in the filter region of the proteins at warm temperatures. In the opinion of the authors, quantum mechanical properties are necessary to explain a fundamental biological property, such as ion selectivity in transmembrane currents and the effect of gating kinetics and shaping of classical conductances in electrically excitable cells.

It should be noted that the very existence of quantum effects in vibrations of molecules or in condensed media is not something special, often only leading to a decrease in heat capacity. It remains unclear, however, how important such an effect is for individual neuron

function as a whole and whether it will have any consequences for brain function and thinking.

Hu and Wu (2004) have suggested that the spin states of nuclei within molecules (H[1], C[13], P[31]) that make up neural membranes changes as an action potential passes along them. The authors note that nuclear spins interact with each other through dipole interactions and via J-coupling (indirect dipole-dipole coupling). This interaction strongly depends on the conformation of the molecules in the membrane. In this case, the frequencies of the spin interactions of some nuclei roughly coincide with the characteristic frequencies observed for neural function. It remains unclear how large such an effect is. Can it in reality change the conformation of biologically important molecules?

The quantum Zeno effect was considered by several authors as one of the mechanisms for the connection between consciousness and the brain. Such a mechanism is considered, for example, in the works of Stapp (2004), Georgiev (2015). In the model of the brain's Stump, an *n*-dimensional quantum system is modeled, the evolution of which is described on the basis of the density matrix.

In a paper (Georgiev, 2013) it is shown that identification of mind states with quantum states within the brain is biologically feasible. The author believes that quantum theory might have profound implications for the scientific understanding of one's mental states, self-identity, beliefs and free will.

Georgiev (2017) summarizes the approaches considered earlier. In particular, the following axioms are formulated: to each mind there corresponds a wave function, there is an energy threshold for the reduction of the wave function. The author notes that the brain cannot be entangled with other organs; otherwise, we would have noticed it immediately, but individual neurons could be in a coherent state. According to the author, the ensemble of neurons makes a decision before such an entangled state disintegrates. In this case, the entanglement-disentangling cycles must be very fast - their frequency should be greater than 100 GHz. That is, consciousness should take 10^{-11} seconds.

It remains unclear what can happen in such a time and how to verify it, as this time is on the order of the vibration of atoms. Even a nerve impulse takes milliseconds and is comparatively very slow. Within this time period, light would pass only 3 mm.

The application of Bohm's version of quantum mechanics to the processes of thinking is utilized because the pilot wave (on the concept of which Bohm's quantum mechanics is largely based) itself can to some extent be considered the simplest form of consciousness. For example, Pylkkanen (2016) believes that certain properties of quantum systems can help to understand the properties of consciousness. The pilot wave carries active information and, in a sense, informs the particle about its surroundings. According to the author, consciousness exists only because there is a higher level of information. This last remark can be attributed not only to consciousness but also to thinking in general. However, it is necessary to specify what is meant by such a higher level of information. What, in particular, is the carrier of such information? The model constructed below aims to answer this question.

According to Geesink and Meijer (2018) nature organizes animate and inanimate components at coherent way, able to unite first, second, third and higher harmonics. The authors proposed arithmetical 12-number scale with 12 sequences of unique products of integer powers of 2, 3 and a factor and can be regarded as eigenfrequency functions. The discovered frequency patterns can be interpreted as hidden variables in Bohm's causal interpretation of quantum mechanics theory.

Thus, based on an analysis of the role of quantum mechanics in neural function, it can be concluded that such effects in neurons and the brain are substantially limited by the process of decoherence. Without additional assumptions, it is not possible to explain why decoherence may be sufficiently weak. Otherwise, the quantum effects of neural function will be negligible.

3. Quantum model of morphogenesis and formation of connections between neurons

The formation of new synaptic contacts between neurons (or their destruction) is one of the most important processes in neural function. Extensive literature is devoted to this subject (see, for example, Sanes and Lichtman, 1999; Huttenlocher and Dabholkar, 1997; Suzuki et al., 2007; Kutsarova et al., 2017).

For example, mammals are able to create new neural connections, unlike species with stable connections. These connections are created as the world around us affects our senses, which send the appropriate electrical impulses to the brain. These impulses pave the neural pathways through which other nerve impulses will move more rapidly and easily in the future. That is, the brain of each individual person is tuned to an individual experience.

A constantly working neuron over time is covered with a shell of myelin, which significantly increases the efficiency of the neuron as a conductor of electrical impulses (see, for example, Arancibia-Carcamo et al., 2017). Myelin covers neurons at the age of two, as the body learns to move, see and hear. When a mammal is born, a mental model of the surrounding world should be formed in its brain, which will provide opportunities for survival. Therefore, the production of myelin in a child is maximal at birth, and by seven years it is somewhat reduced. Learning new skills is largely related to myelinated neural connections (McKenzie et al., 2014).

New neural dendrites are formed via active stimulation by electric pulses. As dendrites grow in the direction of electrical activity, the electrical impulse from other neurons can overcome the distance between them and new synaptic connections arise. Are synaptic connections and ideas somehow related to each other?

In the hippocampus, an adult develops approximately 700 new neurons daily (Spalding et al., 2013). According to the authors this number decreases with age, but not significantly. Thus, neurons are regenerated in the olfactory bulb and in the human hippocampus. After differentiation for a short time, new neurons have increased synaptic plasticity. These two areas of the brain have a large number of neuroblasts immediately after birth that is significantly reduced after the first year of life, and in the process of maturation, there is a moderate decrease in their number.

Neurogenesis of the adult brain creates new neuronal networks in the place of damaged ones, which plays an important role in the repair of the damaged brain, as well as in its plasticity.

Thus, neurogenesis, as well as the formation of new connections between neurons, is the most important component of neural function. This process can be considered as a variant of morphogenesis, since it is very similar to the processes of formation of other organs and tissues.

As noted above, one of the most important motivations for applying quantum mechanics to the operation of the brain is to understand the interaction between biologically important molecules and the problem of protein folding. These processes play a highly important role in morphogenesis.

When applied to neurons, the issues with models that describe morphogenesis in the absence of long-range forces are expressed in the fact that the formation of new synaptic connections would not be possible, as there is no way to choose the correct molecular state among an almost infinite number of irregular ones. In this sense, the two neurons, between which a new synaptic contact should form, can be regarded as two complex biologically important molecules. The problem of a large number of conformational degrees of freedom in this case is only aggravated, since the formation of such a contact requires the coordinated work of many proteins and other macromolecules.

Based on this understanding, a quantum model of morphogenesis was constructed in Melkikh and Khrennikov (2018), which can also be used to model neural function. Within the framework of the model, the concept of *internal control* is introduced. This term is understood as the control of particle motion at the quantum level. In many ways this

concept is a generalization of the term *internal measurement*, introduced earlier for biosystem modeling (Matsuno, 1996). In the latter case, it is implied that the collapse of the wave function (measurement) leads to definite states of the system. In the work (Melkikh and Khrennikov, 2018), it was suggested that not only does collapse occur in well-defined states, but within the system, there are quite definite mechanisms of controlling collapse (decoherence).

The most famous Turing model (Turing, 1952), used for modeling morphogenesis, is a system of equations:

$$\frac{\partial u}{\partial t} = \gamma f(u, v) + D_u \Delta u$$

$$\frac{\partial v}{\partial t} = \gamma g(u, v) + D_v \Delta v$$

where the functions $f(u, v)$ and $g(u, v)$ are responsible for the kinetics of the reactions between substances u (activator) and v (inhibitor), D_i are the diffusion coefficients of substances, and γ is the scale factor.

However, such a system of equations has a significant drawback, which follows from the fact that it is not enough for molecules to meet so that a completely definite reaction between them takes place. It is also necessary that the conformational degrees of freedom (which are the greater, the more complex the reacting molecules) also come to a definite state. Thus, for biologically important molecules, the equations of chemical kinetics represent only a rough approximation, which does not say anything about the characteristic times of the processes. In the paper (Melkikh and Khrennikov, 2018), a variable ξ is introduced to describe such processes, which is responsible for the internal degrees of freedom of the reacting molecules (α), and for their spatial position (x):

$$\xi = \xi(x_1, \dots x_n, \alpha_1, \dots, \alpha_m)$$

The kinetics of biochemical reactions will be determined by the spatial coordinates and coordinates ξ, for which the master equation can be written:

$$\frac{\partial p_n(\xi)}{\partial t} = \sum_m^{max} W_{mn} p_m - \sum_m^{max} W_{nm} p_n \tag{3}$$

Such an equation can be obtained on the basis of Eqs. (1) and (2) in the usual way. The probabilities of W_{mn} transitions can, in general, also depend on the coordinates of other biologically important molecules in the cell (and possibly beyond). Thus, the general form of the reaction-diffusion equations between the substances u and v will be as follows:

$$\frac{\partial u(\xi)}{\partial t} = \gamma f(u, v, \xi) + D_u \Delta u$$

The presence of the variable ξ in this equation means that a *quite definite* reaction between these substances will depend substantially on their conformations. In accordance with Melkikh and Khrennikov (2018), we denote by $\xi *$ the state of the variable ξ corresponding to the native conformation of the macromolecule (or the biologically functional state of the reacting substances, such as protein-protein and protein-ligand). Only at this value of ξ can the reaction be considered fulfilled, at all other values it can be said that the substances are eliminated from the game, since they are not able to perform useful work (the probability that the substances will be useful will be small).

Thus, a system of Turing equations with allowance for long-range effects can be transformed to the form:

$$\frac{\partial u(\xi_u)}{\partial t} = \gamma f(u, v, \xi_u) + D_u \Delta u,$$
$$\frac{\partial v(\xi_v)}{\partial t} = \gamma g(u, v, \xi_v) + D_v \Delta v,$$
$$\frac{\partial p_n(\xi_u)}{\partial t} = \sum_m^{m_{max}} W_{mn}(\xi_u) p_m(\xi_u) - \sum_m^{m_{max}} W_{nm}(\xi_u) p_n(\xi_u),$$
$$\frac{\partial p_n(\xi_v)}{\partial t} = \sum_m^{m_{max}} W_{mn}(\xi_v) p_m(\xi_v) - \sum_m^{m_{max}} W_{nm}(\xi_v) p_n(\xi_v). \tag{4}$$

The system of Eqs. (4) explicitly contains long-range interactions, resulting in the formation of synaptic connections (as well as changes in

the shape of the neuron). This occurs depending on the state of not only neighboring neurons but also many other (more distant) neurons.

Long-range action within the framework of this model can be manifested in the fact that the forces of interaction between biologically important molecules are non-Archimedean. Non-Archimedeanness is a consequence of the violation of the principle of superposition for vectors and violates the well-known triangle inequality. Non-Archimedean analysis has found wide applications in various fields of mathematics, physics and biology (see, for example, Khrennikov, 2004).

Important properties of long-range quantum fields are topological. The importance of topology in protein folding and chemical reactions between biologically important molecules was previously considered (Melkikh and Meijer, 2018). With respect to the operator φ, this means that there are additional rules for inhibiting the dynamics of biologically important molecules associated with preventing the formation of undesirable knots. The role of such knots in this case is played by "parasitic" reactions between different proteins. As a result, only the formation of "right" bonds is permissible. From the topological point of view, the motion of a biologically important molecule within a neuron or between neurons is a series of homeomorphic (in some sense equivalent) states. In this sense, the dynamics of biologically important molecules can be called homeomorphic.

In fact, the movement of biologically important molecules in such quantum fields will be a sequence of operations on numbers (coordinates and impulses), which somewhere must be encoded. Such information (considered as a text or a program) can be regarded as complementary to the genetic one.

Thus, the formation of neurons from stem cells, as well as the formation of new synaptic connections between neurons, are processes controlled by long-range forces. These forces themselves cannot be justified within the framework of classical mechanics (see Melkikh and Meijer, 2018 for more details) and should be a purely quantum phenomenon.

4. Quantum model of neuron function and the problem of learning

In addition to the formation of new synaptic contacts, other important properties of neurons that largely support the process of thinking are neuroplasticity (change in the weights of synaptic contacts), as well as the work of the cytoskeleton, neuroreceptors, and others.

Decision-making and recognition are often described with the help of artificial neural networks, the very origin of which is largely due to the similarity to the structure of the brain.

To model the thinking processes, we will start with the neural network paradigm, taking into account, on the one hand, that the real neuron demonstrates a much more complex behavior than the artificial one. On the other hand, we will take into account the quantum processes in the behavior of biologically important molecules discussed above (Section 2). According to the neural network paradigm, a neural network consists of formal neurons that form several layers. The scheme of the formal neuron is shown in Fig. 3.

Fig. 3 Of course, brain neurons are in many ways different from formal neurons. In particular, a more detailed study of neurons leads to the following conclusions:

- there is a direct link between the specific synaptic input pattern, the mode of dendritic integration, and ultimately the form of action potential output processing in the dendrites (see, for example, Gasparini and Magee, 2006);
- neuron now considered as a processor with mixed analog-digital logic and highly adaptive synaptic elements (Koch and Segev, 2000);
- axons achieve several fundamental operations that go beyond classical propagation, for example, axonal propagation might also 'bounce back' (see, for example, Debanne, 2004);
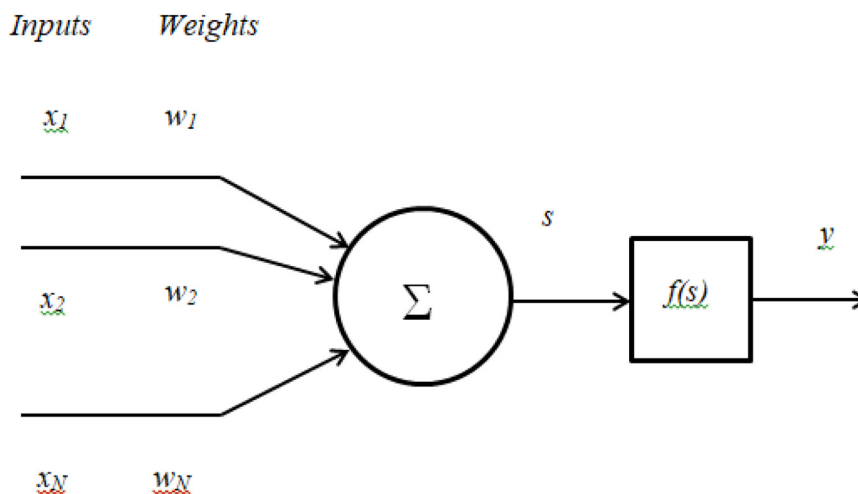
Fig. 3. Formal neuron scheme.

- The axon of a real neuron splits to a large number of axonites, which connect it to secondary neurons (Cottam and Ranson, 2017). Pribram (2001) proposed that quasi-waves in 'axonite mesh' transmit a superposition of the primary-neuron outputs to the secondary neuron dendrites in a manner which is analogous to the collapse of the wave function in quantum mechanics.

The work of a formal neuron is based on a transformation of type (nonlinear weighted sum):

$$y = f\left(\sum_i w_i x_i\right) \tag{5}$$

f – is an activation function, x_i – are inputs, y –is output, w_i – weights of synapses.

The learning rule modifies the parameters of the neural network in order to obtain the desired output based on this input. In artificial neural networks, training is carried out in a special mode - training with the teacher. In this mode, some external source (teacher) should explicitly indicate which outputs correspond to some examples (training sample). As methods of training artificial neural networks, for example, the method of back propagation of errors is used.

It should be emphasized, however, that in living systems, learning is a fundamentally different process, since the teacher does not have direct access to neurons and the synaptic contacts between them. The teacher, as well as any part of the surrounding reality is perceived by man only with the help of receptors - and this is a fundamentally different process. As was shown earlier in several works (see, for example, Melkikh, 2014b; Melkikh et al., 2018), what we call training in life actually has nothing to do with training the neural network. To solve the learning problem, it was assumed that all behavioral programs are congenital. At the same time as a result of training only the launch of such innate programs possible.

Thus, the process of tuning the synaptic weights during brain operation must occur in parallel with the decision-making process, and the tuning process itself must be of an intrinsic nature. The weight of the synaptic connection is somehow determined by the structure of the proteins that make up the synaptic contact. Therefore, based on the model of interactions between biologically important molecules considered above, we can write:

$$\frac{\partial p_n(\xi_{X12})}{\partial t} = \sum_m^{m_{max}} W_{mn}(\xi_{X12}) p_m(\xi_{X12}) - \sum_m^{m_{max}} W_{nm}(\xi_{X12}) p_n(\xi_{X12}) \tag{6}$$

Here, X is a set of innate behavioral programs, the physical realization of which is the quantum state of biologically important molecules. Indices 1 and 2 refer to neurons, between which a synaptic contact is

established. Eq. (6) describes the directed evolution of the synaptic coupling force.

We note that the importance of the topological properties of quantum fields, noted above, also holds here. This means that the state of the synaptic contact (and the neuron as a whole) is determined by the nontrivial (topologically dependent) state of all of the molecules that make up the neuron, and possibly also the molecules outside of it. That is, the state of ion channels, G-proteins, microtubules, synaptic vesicles, and other internal neuronal structures ultimately determines the state of a synaptic contact between two specific neurons.

The connections between this large number of molecules (not only inside one neuron but also between neurons) generates a new network that is essentially quantum in nature. This network processes signals that are most likely unconscious, and the results of processing can be attributed to the subconscious.

An elementary mental event in this case is the exchange of a virtual particle between biologically important molecules. It should be emphasized that the uncertainty principle is only applicable to real particles (see, for example, Melkikh, 2017), i.e., until real particles are emitted or absorbed, the uncertainty principle cannot be applied. This means that if the control itself contains only virtual particles, then no restrictions can be imposed on it. Additionally, no matter how the signals are processed by virtual particles, sooner or later they must affect real particles. These real particles can be part of classical effectors or other parts of the body.

5. Innate programs of behavior and quantum metalanguage

In addition to the interaction between biologically important molecules, there is another important motivation for applying the laws of quantum mechanics to neural function. This motivation is the problem of knowledge acquisition. Earlier works (Melkikh, 2014b; Melkikh et al., 2018) show that the acquisition of knowledge is contradictory, which is reflected in the fact that

- All behavior programs are congenital,
- Abstracting and creating new concepts are contradictory. Contradiction is expressed in the fact that a new concept must exist before its creation,
- The language in which we speak is innate,
- The Bayesian method of learning can be effective only if there are good hypotheses that are congenital,
- Congenital behavior programs allow behavior to be flexible due to multiple type structures if … then ….
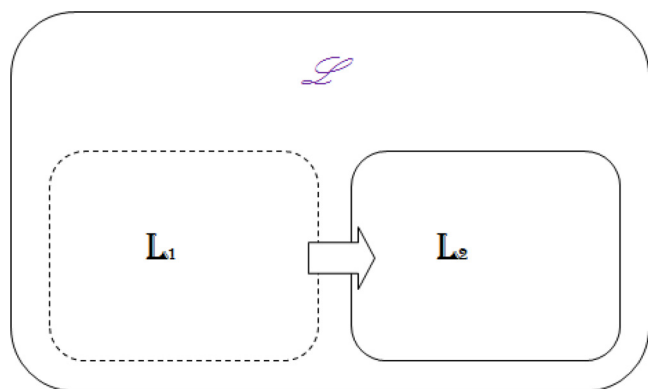
Fig. 4. Structure of the quantum metalanguage.

To solve the problem of knowledge acquisition, the concept of *quantum metalanguage* is used (Melkikh and Khrennikov, 2018, see also Zizzi, 2012). Metalanguage is a language of a higher level, which works with other languages. Some operations within quantum metalanguage can be used to generate new languages from given languages, including replenishing them with new terms, symbols, etc.

In recent work (Melkikh et al., 2018) it is assumed that it is precisely such operations that are defined over our language. These operations are defined in some higher-level language *L* (Fig. 4).

Language L_2 (which we use) is constantly replenished due to the innate quantum language L_1 according to the rules of language *L*. Thus, we can build the following logical chain, modeling thinking:

Changes in the environment → change registration by receptors → recognition with the L_2 language → if not → recognition with the metalanguage → operations over the L_2 language involving the image, such as generalization, the formation of new concepts → the insertion of a new character in the L_2 language (together with the possible operations on this character) → "new" knowledge.

Quantum mechanics represents the natural conditions for the formulation of the metalanguage - the discreteness of energy and states. Within the framework of quantum mechanics of particles, the set acts as a language:

$$\{\Psi, \hat{H}\}.$$

That is, the Hamiltonian can be considered as a set of operations on wave functions. However, generally speaking, in order to construct a quantum model of an arbitrary system, it is necessary to take into account the quantization of fields.

According to (Melkikh et al., 2018), the metalanguage operates in a more general space, part of which is the Hilbert space of wave functions. The elements of the metalanguage can also be birth and annihilation operators applied to various elements of the language. With the help of such operators in the language, new concepts and ideas are *selected* from a list of a priori existing concepts.

For effective functioning, a quantum metalanguage must have a large information capacity, that is, an order of magnitude greater than the capacity of any of the known languages. According to Melkikh et al., 2018, such a requirement contradicts the comparatively small information capacity of genes. Indeed, genomes of higher organisms contain only about a gigabyte of information, which is clearly not enough to manage such complex behavior as human. This apparent contradiction can be solved on the basis of the assumption that the interaction between biologically important molecules (including those within neurons) is an essentially quantum effect. As it was mentioned above, long-range potentials allow modulating the movement of biologically important molecules. This additional interaction allows an increase in the information capacity of molecules by orders of magnitude, as well as the neuron as a whole, which is not directly related to genes.

6. Physical basis of thinking: topology, sets and control

Thus, elementary acts of interaction between biologically important molecules that lead to the formation of new complexes and mechanical motion can be considered as the physical basis of the quantum metalanguage. In this case, the controlling quantum system (internal control) will play the role of "teacher" for the neural network. In a sense, the teacher in this case is the quantum metalanguage, since the replenishment of our language with new symbols and concepts is quite consistent with the recording mode in the neural network.

As noted in the work (Melkikh, 2018), the proposed model is an extension of quantum mechanics, in particular, in the non-Archimedean space the concept of "distance" changes significantly (see, also Khrennikov, 2004). In relation to biologically important molecules, this property is fundamental, since it can provide long-range interaction. It was noted (Melkikh, 2018) that topological operations are also more general than operations on a wave function in a metric space. This is manifested in the fact that the metric space itself is a special case of topological space (see, for example, Viro et al., 2008). On the other hand, dynamics in a metric space can be generalized using the term "mapping". The mapping of a set X (according to Viro et al., 2008,) into a set Y is a triplet composed of X and Y and a rule that assigns to each element of the set X an element of the set Y:

$$f: X \rightarrow Y$$

According to (Melkikh, 2018), such a mapping can be interpreted from a dynamical point of view as follows:

$$f: X(t) \rightarrow X(t + \tau) \tag{7}$$

Here τ - is some characteristic time. In this case, the homeomorphic transformation is more general than a unitary evolution. If we consider the wave function as a set, then the unitary transformation

$$\Psi(t + \tau) = \hat{U}\Psi(t)$$

will always be a homeomorphism, but the reverse is not true.

In the case of unitary evolution in quantum mechanics, the purity of state is the invariant, but if we consider the wave function as a topological object, then more general properties of the wave function, such as the connectivity or the number of dimensions will be invariants.

Topology has shown its utility, for example for modeling topological quantum computers (see, for example, Trebst et al., 2008; Wootton et al., 2014; Nigg et al., 2014).

The foregoing allows us to assume that the interaction between biologically important molecules (in particular, responsible for the brain) is determined by homeomorphic transformations of the type (7), in which the wave function appears as the *set*.

The use of the most general formalism of set theory in relation to biologically important molecules that provide the work of the brain makes it possible to directly connect the brain and thinking. Indeed, on the one hand, the dynamics of biologically important molecules is described on the basis of set theory, but on the other hand, it is with the help of these molecules these concepts of set theory can be formulated. In this sense, the most common at the present time is the Zermelo-Fraenkel axiomatics, which describes, in this case, both the quantum fields themselves and the abstractions realized on their basis (Fig. 5).

A similar property - duality - occurs in *category theory* (see, for example, Awodey, 2010).

The problem of tachyons also adjoins the problem of long-range interaction. For example, in the paper (Hari, 2011) possible role of tachyons in the work of the brain is considered. As is known, tachyons do not fit into the standard model of elementary particles, but some researchers consider the possibility of their existence. The author considers tachyons as mental units. Tachyons, in this case, act as an algorithm, and quantum potential acts as a program. The brain and the constituent neurons act as a "hardware". In this way, the author tries to solve the problem of how thinking acts on the brain and vice versa.
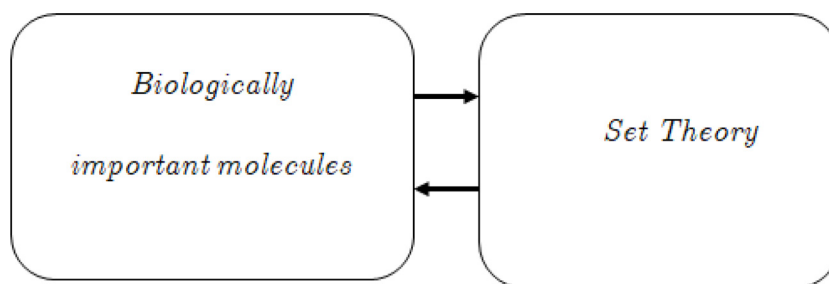
Fig. 5. Connection between the brain and thinking.

In accordance with what was said above, it is topological quantum field theory (TQFT) that is promising for modeling neural function and consciousness. This theory should explicitly include the specific topology of biologically important molecules, as well as brain symmetry.

Thus, since these processes are interrelated, the entire neural network can be relatively arbitrarily divided into quantum and classical subsystems. The classical subsystem includes the neurons themselves and the action potential transmitted between them. The quantum subsystem includes processes of interaction of biologically important molecules in neurons that produce fine control of the classical subsystem. Of course, the action potential is determined by the opening and closing of ion channels (although there is another view of this phenomenon associated with purely mechanical membrane ordering processes (see, for example, Heimburg and Jackson, 2005), and in this sense is related to the work of biologically important molecules. However, the potential itself is described on the basis of classical electrodynamics.

In light of what has been said, the question arises as to which structures of the brain quantum behavior should be characteristic of. Note that the problem of interaction between biologically important molecules is of a general nature and should be characteristic of all components of organisms, such as cells, organs, and tissues. That is, quantum properties are inherent in the whole brain. Only for some of its parts do they appear in such processes as thinking and abstraction. For other parts, these properties are manifested in the stable operation of the molecular control of reactions within the organism. These reactions can, in a sense, also be regarded as a metalanguage.

Neurons, while performing their functions, can be regarded as analogues of protein molecules: protein molecules consist of the same amino acids, but they differ in their spatial configurations and functions. The same can be said about neurons - it is quite possible that the neurons of the human brain do not fundamentally differ from the neurons of other animals, but their unique configuration (taking into account the unique configuration of intraneuronal biologically important molecules) can provide the unique property of the brain - thinking.

In this connection, the question arises as to which processes we are conscious of and which processes we are not. Since we cannot trace the mechanism of the emergence of new concepts (and in general new knowledge), it is natural to assume that the quantum control system is not conscious. For the classical subsystem, it is most likely partially and not necessarily conscious. For example, there are experimental data showing that at rest (during sleep) the brain is almost as active as during complex operations (see, for example, Raichle, 2010).

There exists a special system that removes the products of vital activity from the brain. For example, over the course of a month, more than 100 g of waste substances are formed in the brain (see, for example, Plog ang Nedergaard, 2018). The damaged proteins are replaced with new ones. It was found that the activity of such a system is higher during sleep. There is no lymphatic system in the brain, but instead there is a glymphatic system (see, for example, Jessen et al., 2015). Disturbances in these systems are associated with Alzheimer's and Parkinson's diseases. From the point of view of the model proposed in this article, this means that during sleep some of the biologically important molecules involved in the processes of thinking do not work because of the need for their repair. Errors in the work of such molecules are inevitable, since the energy of interaction between them is finite. Therefore, certain of the thinking processes fail.

The question arises of how to register a quantum control system and, in general, quantum effects in the work of neurons. In relation to biologically important molecules, a number of such possible experiments were proposed earlier (Melkikh, 2014a; Melkikh and Meijer, 2018). In relation to neurons, the purpose of such experiments is the identification of innate programs of behavior. This can be done by tracing the entire decision-making process at the molecular (atomic) level: changes in the environment → recognition → decision-making → action. At present, researchers mainly use a much coarser scale, in which only the neuronal nerve impulses are fixed. Experiments at the molecular level are a great difficulty, as they must be carried out on the working brain. With the help of such experiments (using, for example, luminescence methods or a free-electron laser), one can find quantum effects in the work of neurons. Further development of experimental equipment can make such experiments possible in the coming decades.

7. Conclusions

Neural function can only be consistently described on the basis of quantum mechanics. The processes of thinking, based on the work of neurons, can be modeled on the basis of the ideology of neural networks. However, in this case, there is an essential feature in the brain: the standards for neural networks are congenital. The process of tuning the synaptic weights during brain operation must occur in parallel with the decision-making process, and the tuning process itself must be of an intrinsic nature. This process involves long-range quantum forces acting between biologically important molecules. A model of thinking based on the use of quantum metalanguage is constructed. Within the framework of the model, the wave function of molecules that realize the quantum metalanguage should be considered to be a topological object.

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