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Can the human brain do quantum computing?

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Summary The electrical membrane properties have been the key issues in the understanding of the cerebral physiology for more than almost two centuries. But, molecular neurobiology has now discovered that biochemical transactions play an important role in neuronal computations. Quantum computing (QC) is becoming a reality both from the theoretical point of view as well as from practical applications. Quantum mechanics is the most accurate description at atomic level and it lies behinds all chemistry that provides the basis for biology ... maybe the magic of entanglement is also crucial for life. The purpose of the present paper is to discuss the dendrite spine as a quantum computing device, taking into account what is known about the physiology of the glutamate receptors and the cascade of biochemical transactions triggered by the glutamate binding to these receptors.

Introduction

Quantum computing (QC) is a reality from the theoretical and practical points of view. New techniques are turning quantum operations feasible [1–3], ion traps (IT) among them [1–6]. In IT ion trap experiments, quantum bits (qubits) are formed from the electronic states of trapped ions and coupled through the Coulomb interaction [3–6]. The brain is the most sophisticated processing machine developed by nature so far, and QIC has been considered to model its function [7–9]. Dendritic spines (DS) are specialized synaptic structures (see Fig. 1) allowing large, extremely rapid, long lasting and localized [Ca^{2+}] build up at the spine [10–13]. They are very plastic structures [14,15] involved in both rapid (imprinting) and slow learning [16–19]. Quantum Mechanics is the most accurate description at atomic level and it lies behinds all chemistry that provides the basis for biology ... maybe the magic of entanglement is also crucial for life [20]. In line with this reasoning, we propose DS as IT devices and discuss how it can solve the Deutsch-Jozsa algorithm [1,6,21] (DJA).

Basic to the understanding of DS as a quantum IT device is the physiology of the glutamate (Glu) and its receptors (Fig. 1) [22–25]:

(a) *AMPA receptor*: the Glu-binding to AMPA allows the entry of Ca^{2+} and promotes a depolarization of the membrane potential (EM), what facilitates Ca^{2+} entry through the voltage sensitive Ca channels (VSCCs in Fig. 1);

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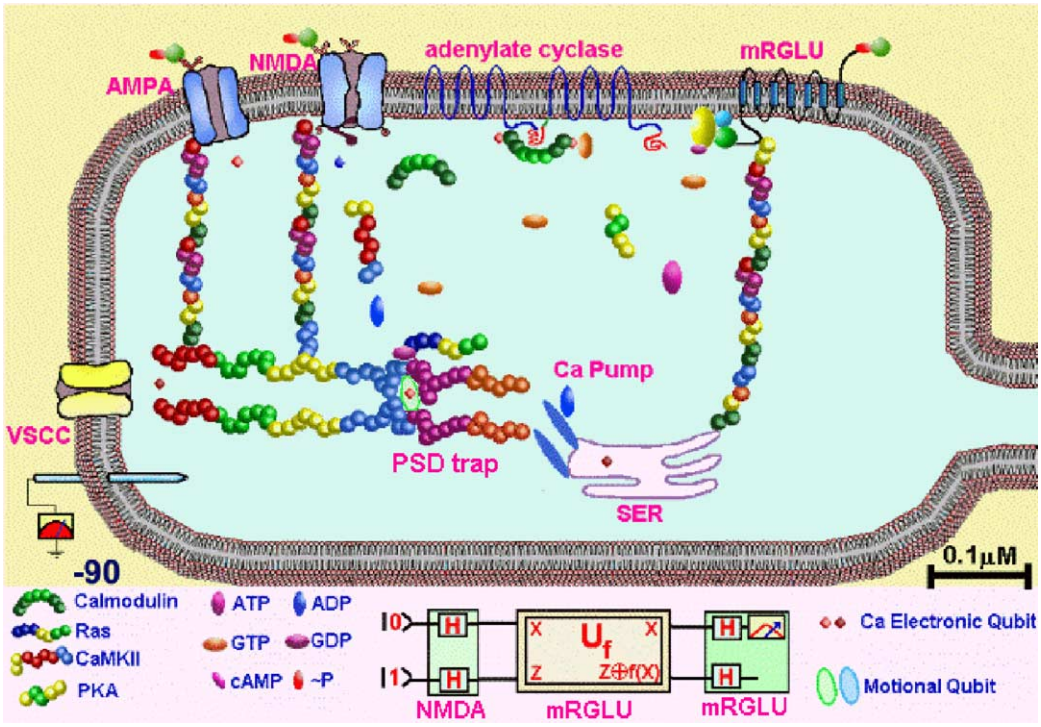

Figure 1 Stepl: Glu binding to the AMPA receptor and allows Ca^{2+} to move into the dendritic spines through AMPA and VSCC channels. Ca^{2+} entering this latter channel is trapped in a narrow molecular cavity formed by PSD proteins. Step 2: Glu binding to the NMDA receptor allows Ca^{2+} to enter the spine and to bind to Calmodulin in order to activate CaMKII, which in turn activates RAS that under GAP action liberates energy to performed a Hadamard gate. Steps 3 and 4: Glu binding to mRGLU activates a G-protein to stimulate Adenylate Cyclase to produce cAMP, which is used to activate PKA. PKA controls RAS to first implement U_f and then to perform another Hadamard gate. Step 4: Finally, the trapped Ca^{2+} is moved into the smooth endoplasmic reticulum (SER) by cAMP activated Ca^{2+} pumps. For details, please see www.eina.com.br/sensor.

(b) *NMDA receptor*: functions as a coincidence detector (CD), since the AMPA EM depolarization remove the Mg^{2+} attached to it, and a posterior Glu-binding within a temporal window (100 ms), allows new Ca^{2+} to move in and to bind to calmodulin, that controls the CaMKII kynase to deliver energy to other biochemical processes;

(c) *mR-Glu receptors*: Glu-binding to mRGlu activates many types of **G-proteins** controlling other cellular processes. G-protein is a CD too ($\Delta = 200$—600 ms). A set of proteins [22,23] anchors Glu-receptors in the membrane by (Fig. 1). Ca^{2+} concentration inside the cell is controlled by pumping it outside the cell or to organelles (e.g., SRE in Fig. 1).

Deuthsch-Jozsa's algorithm (DJA) was the first explicit example of a computational task performed exponentially faster using quantum effects than by classical means [1,6,21]. Given a one-bit function, f one have:

(a) two constant functions $f(0) = 0$ and $f(1) = 0$, or $f(0) = 1$ and $f(1) = 1$; or

(b) two "balanced" $f(0) = 0$ and $f(1) = 1$, or $f(0) = 1$ and $f(1) = 0$.

A one qubit QC (Fig. 1(b)) is able to decide if f is constant or balance in just one step. Starting with the standard state $|0\rangle|0\rangle$ at the input (I) and output (O registers, a NOT operation is applied to I and the Hadamard transformation (H in Fig. 1) is applied to both registers. Thus

$$|0\rangle|0\rangle \overset{\text{NOT}}{\rightarrow} |0\rangle|1\rangle \overset{H}{\rightarrow} \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)\left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right). \tag{1}$$

Next, the unitary transformation U_f is applied to both registers

$$U_f : \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)\left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right) \rightarrow \left(\frac{1}{\sqrt{2}}\sum_{x\in B}(-1)^{f(x)}|x\rangle\right)\left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right). \tag{2}$$

In this condition, O remains in the state $(|0\rangle - |1\rangle/\sqrt{2})$ and I is left in the state. Therefore,

if f is constant I is $\pm(|0\rangle - |1\rangle/\sqrt{2})$ and if f is "balanced" it is $\pm|0\rangle + |1\rangle/\sqrt{2})$. If H is applied again to I, it becomes $\pm(|0\rangle)$ if f is constant and $\pm(|1\rangle)$ if f is "balanced". These states are reliably distinguished by a measurement in the standard basis, thus distinguishing balanced from constant functions after just one query. DJA was implemented in a Ca^+ ITC [6].

Basic concepts of quantum computing

Two of the most surprising properties of quantum systems are *state superposition* and *entanglement*. Superposition is the coexistence of different state values of the same particle at the same time. Superposed states are reduced to a single one by the act of measurement or by other kinds of interaction with the macro-environment, which are called *decoherence*. Entanglement is a strong state correlation between spatially separated particles. It is an experimental finding still not explained in terms of causal processes based on electromagnetic or gravitational forces. One interpretation of the phenomenon is that entangled particles behave as a single being, despite their distributed spatial location.

Quantum computing is a research area devoted to experimentally manipulate the superposition and entanglement of states, and to develop algorithms that could be implemented in such quantum systems. While entangled, two or more particles have correlated superposed states (e.g., spin up and down). Therefore, by measuring one particle and reducing its state to a single one (e.g. spin up), we gain knowledge about the actual state of the spatially separated entangled one(s) (e.g., spin down). This is equivalent to obtaining two bits from one. Quantum computation uses the concept of a quantum bit (*qubit*), which is equivalent to a superposition of quantum orthogonal states, i.e., n qubits corresponds to 2^n superposed states. Entanglement of two particles generates two qubits, corresponding to four classes of possible states, which are called *Bell states* [1–3]. A qubit can be in any state:

$$\alpha|1\rangle + \beta|0\rangle, \tag{3}$$

where α and β are complex numbers called amplitudes, subject to

$$|\alpha|^2 + |\beta|^2 = 1. \tag{4}$$

Measurement on $\alpha|1\rangle + \beta|0\rangle$ results in the qubit making a probabilistic decision with probability $|\alpha|^2$, it becomes $|0\rangle$ and with complementary probability $|\beta|^2$, it becomes $|1\rangle$.

As physical system of n qubits requires 2^n complex numbers to describe its state, two qubits can be in the Bell states:

$$\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \tag{5}$$

such that

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1. \tag{6}$$

Let a quantum computer **QC** be defined by Eqs. (5) and (6). A given instruction i_i may be written on it by, e.g., changing its state to

$$\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle - \delta|11\rangle, \tag{7}$$

that is, by modifying the condition of qubit $|11\rangle$.

The change influences the entanglement of this qubit with the other ones. QC is based on such an interference of qubits, which has been proved of being able to perform classical logical gates and also other ones, called *quantum gates*.

The only constraint on quantum gates is *unitarity*, which is based on the constraint **4**. Therefore, "any unitary matrix specifies a valid quantum gate!" [1,2]. An important operation is the Hadamard gate, by which $|0\rangle$ is changed into $(|0\rangle + |1\rangle)/\sqrt{2}$ and $|1\rangle$ is changed into $(|0\rangle - |1\rangle)/\sqrt{2}$. Applying the Hadamard gate twice to a qubit generates an output that is identical to its initial state.

According to Nielsen and Chuang [1], a QC has five requirements:

(a) having two parts, a classical and a quantum one. Although the classical part is not necessary, in practice it is useful in order to specify in binary logic the inputs and outputs to and from the quantum part;
(b) a suitable state space. For n qubits the corresponding state space is a 2^n-dimensional complex Hilbert space;
(c) the ability to prepare states in a computational basis (as pure entangled states);
(d) the ability to perform quantum gates, preferably universal gates as the Hadamard and Controlled NOT (CNOT; an equivalent of the classical XOR, or exclusive disjunction) gates; and
(e) the ability to perform measurements in a computational basis.

Therefore, any proposal of biological QC should be able to demonstrate the possibility of a biological structure to fulfill such requirements.

The hypothesis

Conjecture 1. *CD was proposed to create entangled quantum states in the brain [7,8]. The rationality is the following (Fig. 1):*

(1) *A first Glu released binds to the AMPA channel promoting EM reduction, Mg^{2+} release from the NMDA channel, VSCC activation and Ca^{2+} entry. These Ca^{2+}s are physically trapped by proteins in a molecular cavity of typical size of 0.7 Å (bigger than Ca^{2+} radii) in the spine.*
(2) *A second release of Glu within $\Delta = 100$ ms, allows new Ca^{2+} to bind to calmodulin to provide energy to create state superposition and entanglement of the trapped Ca^{2+} ions. The electronic qubits are $|0\rangle = s^1$ and $|1\rangle = 3p^0$ and the required energy is in the band of 50 nm (UV). The motion qubits are $|0\rangle =$ ground state and $|1\rangle =$ first excited state, with ground state energy of 3.2 eV.*
(3) *A third Glu release over mR-Glu within $\Delta > 100$ ms, activates G-proteins to deliver energy to manipulate the entangled Ca^{2+}.*

Conjecture 2. *It is supposed here, that DS process the DJA as follows (Fig. 1). The AMPA channel is associated to O whereas the VSSC is assigned to I. EM depolarization promoted by Ca^{2+} entry through the AMPA channel remove the Mg^{2+} from the NMDA channel and opens VSCCs. Next, NMDA channel are activated, and CaMKII controlled RAS is used to perform the Hadamard transformation upon the Ca^{2+} trapped in the post-synaptic density (PSD). Next, mR-Glu receptor is activated, and a G-protein is used to control the implementation of U_f. The same G-protein controls the energy to perform another Hadamard transformation. Finally the Ca^{2+} transporting into SER is used to read the result. A point worth to remark is that DS is amenable to many different and sophisticated experimental manipulations, see for instance [10—16], that may be used to check these assumptions.*

Now, let's suppose another function $f : B^n \rightarrow B$ that is either constant if the 2^n values are either 1 or 0, or balanced if exactly half (i.e. 2^{n-1}) of the values are 0 and half are 1. DJA [1,21] is extended to treat such kind of function, if one starts with a row of n I qubits and one O qubit and to applies the same step procedures above. At the end, the n is arel in state

$$|\xi_f\rangle = \left(\frac{1}{\sqrt{2}^n} \sum_{x \in 2^n} (-1)^{f(x)} |x\rangle \right) \quad (8)$$

If f is constant then ξ_f will be just an equal superposition for all the $|x\rangle$'s with an overall plus or minus sign, whereas if f is a balanced function then ξ_f will be an equally weighted superposition with exactly half of the $|x\rangle$'s having the minus signs. Recalling that H has its own inverse ($HH = 1$) and that H applied to each qubit $|0\rangle$ of $|\xi_f\rangle$ results in an equal superposition of all $|x\rangle$'s. Therefore, if f is constant then the resulting state is $x = \pm|0\rangle|0\rangle \ldots |0\rangle$, and if it is balanced then $|x\rangle$'s is $x \neq |0\rangle|0\rangle \ldots |0\rangle$. The reading of each of the n qubits completes the measurement. DJA requires O(n) steps to distinguish balanced from constant functions, whereas classical algorithm demand $O(2^n)$steps for the same task. However, a probabilistic algorithm is able to solve the same task in k steps with a probability of $(1 - \zeta)$ for correct answer and ζ less $1/2^k$.

Conclusion

Modern Neurosciences is disclosing the neuron as a very complex biochemical machine, in charge of the huge computations demanded by a brain that steadily evolves to take more and more control over the environment where it lives in. The simple McCulloch and Pits neuron, despite its important contribution to a Theoretical Neurosciences in the early days, is no longer an adequate formalism to help the neuroscientist to understand the complexities of the primate brain. Any process at the cellular level is nowadays understood as a dynamical set of biochemical transactions or *stp*s. Therefore, the development of a coherent theoretical framework to model and include the current accumulated experimental data about the physiology of the neuron, is a must. In addition, Quantum Mechanics is the most accurate description at atomic level and it lies behinds all chemistry that provides the basis for biology... and it may be stated that the magic of entanglement is also crucial for life [20] ... what implies that it is critical to the understanding of the brain physiology.

Quantum mechanics is successful because of the close agreement between its theoretical calculations and experimental measurements. To take profit from such achievements, Neurosciences has to incorporate the formalism necessary to understand the quantum events at the level of the neuron, which in turn is a necessity to the comprehension of the huge computational capacity of the brain. However, there is a long road ahead. The complexity of problems to solve is staggering. For instance, quantum events are very temperature sensitive. How the cell is able to keep quantum coherence long enough to purposeful computations at the body temperature? IT computing is currently built in vacuum and very cooled ions. Ca^{2+} is trapped in the water medium in the dendritic spine. What are the complexities intro-

duced by such a biological approach of the problem? These are some of the initial questions to be both theoretically and experimentally addressed.

The main purpose of this article is to invite both the Quantum mechanics and Neuroscience communities to joint efforts in order to open one of the last frontiers of the human investigation of this amazing machine: the brain.

References

[1] Nielsen MA, Chuang IL. Quantum computation and quantum information. Cambridge: Cambridge University Press; 2000.

[2] Bouwmeester D, Ekert A, Zeilinger A. The physics of quantum information. Berlin: Springer; 2000.

[3] Kielpinski D, Monroe C, Wineland DJ. Architecture for a large-sacel ion-trap quantum computer. Nature 2002;17: 709—11.

[4] Libefried D et al. Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. Nature 2003;422:412—5.

[5] Schmidt F et al. Realization of the Cirac-Zoller controlled-NOT quantum gate. Nature 2003;422:408—11.

[6] Guide S et al. Implementation of the Deutsch-Jozsa algorithm on an ion-trap quantum computer. Nature 2003;421:48—50.

[7] Rocha AF, Pereira Jr A, Coutinho FAB. N-methyl-D-aspartate channel and consciousness: from signal coincidence detection to quantum computing. Prog Neurobiol 2001;64:555—73.

[8] Rocha AF, Massad E, Pereira Jr A. The brain: from fuzzy arithmetics to quantum computing. Berlin: Springer-Verlag; 2004.

[9] Hameroff S. 'Funda-Mentality': is the conscious mind subtly linked to a basic level of the Universe? Trends Cognitive Sci 1998;2:4—6.

[10] Sabatini BL et al. The life cycle of Ca^{2+} Ions in dendritic spines. Neuron 2002;33:439—52.

[11] Sbatini BL, Maravall M, Svoboda K. Ca^{2+} signaling in dendritic spines. Curr Opin Neurobiol 2001;11:349—56.

[12] Holthoff K, Tsay D, Yuste R. Calcium dynamics of spines depend on their dendritic location. Neuron 2002;33: 425—37.

[13] Helmchen F. Raising the seepd limit — fast Ca^{2+} handling in dendritic spines. Trends NeuroSci 2002;25:438—41.

[14] Segal M, Andersen P. Dendritic spines shaped by synaptic activity. Curr Opin Neurobiol 2000;10:582—6.

[15] Lieshoff C, Bischo H-J. The dynamics of spine density changes. Behaviour Brain Res 2003;140:87—95.

[16] Fox K. Synaptic plasticity: the subcellular location of CaMKII controls plasticity. Curr Biol 2003;13:R143—5.

[17] Bischof H-J, Geißler E, Rollenhagen A. Limitations of the sensitive period for sexual imprinting: neuronanatomical and behavioral experiments in the zebra finch (*Faeniopygia guttata*). Behaviou Brain Res 2002;133:317—22.

[18] Segal M, Korkotian E, Murphy DD. Dendritic spine formation and pruning: common cellular mechanisms. Trends NeuroSci 2000;23:53—6.

[19] Lieshoff C, Bischof H-J. The dynamics of spine density changes. Behaviour Brain Res 2003;140:87—95.

[20] Vedral V. Entanglement hits the big time. Nature 2003;425:28—9.

[21] Jozsa R. Quantum algorithms. In: Bouwmeeter D, Ekert A, Zeilinger A, editors. The physics of quantum information. Berlin: Springer; 2000. p. 104—25.

[22] Rocha AF. The brain as symbol-processing machine. Progr Neurobiol 1997;53:121—98.

[23] Ehelers MD. Molecular morphogens for dendritic spines. Trends NeuroSci 2002;25:64—7.

[24] Kasai H et al. Structure—stability—function relationships of dendritic spines. Trends NeuroSci 2003;26:360—8.

[25] Verkhratskt A. The encodolasmic reticulum and neuronal calcium signaling. Cell Calcium 2002;32:393—404.