Why Neurons are Not the Right Level of Abstraction for Implementing Cognition

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Abstract. In their quest for implementing artificial cognition, researchers are trying to look, understand, model and implement (artificial) brain at the neuron level. In this paper, we argue that the neuron is not the right level of abstraction because of its transient activity (spike) and its fatigability. The cortical column – an assembly of about 100 000 neurons – does not exhibit the same limitations. We advocate that the cortical column is Nature's solution to neuron limitations ; and that researchers looking to implement or understand cognitive abilities should be aware of this fact.

1. Introduction

Today's brain projects are becoming more and more frequent; but also more and more expensive. For example, three of the six candidates of the European Commission Future and Emerging Technologies Flagships program (€1 billion in funding over ten years) are explicitly focusing on cognition and the brain. With the "Guardian angels for a smarter life" project, one expects intelligent and direct interactions of the "personal companion" with the human neurological system. The "Human Brain Project" sought to bring together everything known and to be discovered about the inner workings of the brain's molecules, cells and circuits and build a (software) brain simulator. The grand scientific challenge of the "Robot Companions for Citizens" initiative requires and will foster "an advanced understanding of the principles underpinning the mind-body, or structure-function, relationship –or the role of "matter" in building the mind, the principles of neuroscience, and the principles that make living beings cognisant and sentient." The difficulty, and therefore the cost of these projects depends for a large part upon the number of 'logical units' involves – in these cases several hundreds billions (neurons of the human brain).

The cortex is known as the location of cognition. Its building unit is the cortical column – a spatially organized set of about 100 000 neurons. The functional and anatomical existence of the cortical column has been demonstrated as also the uniformity of the cortex organization. Within the human cortex, each cortical column belongs to a cortical map. Cortical maps are hypothesized to number several hundreds.

In the first section, we review neuron (biological) limitations. The following section explains how cortical columns overcome the neuron limitations. The next section discusses how a change in the functional level (from neuron to cortical column) affects the completion of the various 'brain projects' – both at the funding requirements and the delivery dates. Our conclusion points out that the artificial cognition is much closer than usually thought.

2. Neurons

2.1. Transient activity

Neurons are cells dedicated to integrate (compute) and (if necessary) propagate information. The integration part is equivalent to make a decision. Any species (arthropods, worms, amphibians, fishes, birds, mammals, etc.) of the animal realm exhibits neurons. Neurons differ by size, shape, chemical transmitter – but the functioning is sufficiently alike so that the knowledge gathered during the last sixty years though the study the Aplysia giant neurons [1] is useful when it comes to understand mammalian neurons (including human ones). In the same brain, there are dozens of different sets of neurons. The human brain contains about 500 billions neurons. Neurons are living cells, able to transfer (electrical) information to a distance thanks to the fact that they are electrically polarized. 'At rest', they exhibit an electric potential difference of -70 mV with their surroundings (Fig. 1). It does not seem much, but since the cell membrane is only 100 10^{10} m thick, the local electrical field is 70 MV. To stay 'at rest', a neuron consumes lots of energy because ions literally plunge through the membrane, and cells pumps continuously reject them outside, while other pumps get other ions from outside to send them in.

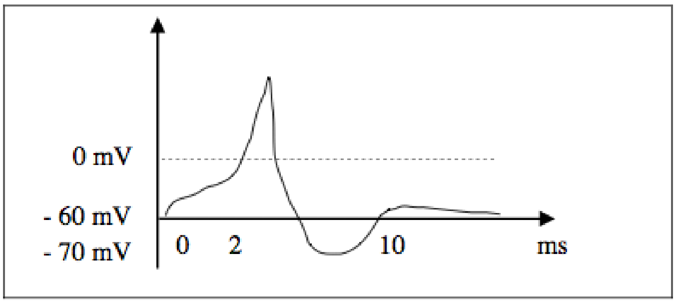

Figure 1. Neuron spike: from -70 mV to +70 mV (in 2 ms) and back to -70 mV (an additional 8 ms).

2.2. Tiredness

Spiking neurons can reach a peak frequency of about 100 Hz. Each discharge consume a lot of energy (glucose) in the sense that after the opening of the membrane gates and the equilibration of the ionic concentrations between in and out of the synaptic membrane, the 'resting' potential difference must be reached again. After a sequence of a few tens of spikes, the neuron stops because of lack of energy (Fig. 2). This huge energy consumption explains why the brain - which only accounts for 2% of the body mass - accounts for 20% of the energy consumption (ten times more than the other tissues).

A spike (discharge) is about 10 ms long, but a new one may occur after only 5 ms. Therefore, in a first approximation, the duration of a burst of 20 spikes (by a unique neuron) is definitely shorter than 0.20 s [2]. Since cognition implies to sustain cognitive activities for usually more than a few seconds, cognitive processes must involve multiple neurons representing the same information.

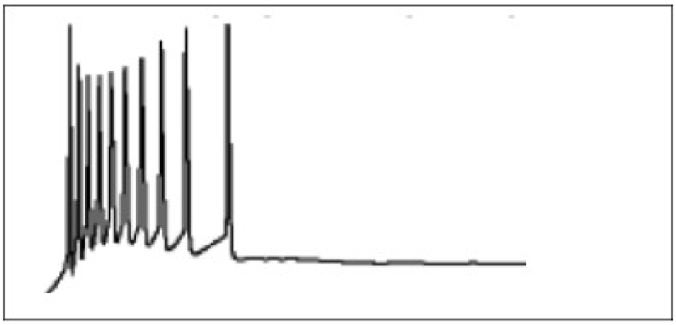

Figure 2. Exhaustion of a thalamocortical neuron after a dozen of spikes (*in vivo* [3]).

3. Cortical Columns

Since a unique neuron is not able to sustain the changes required by cognitive processes, we must infer that multiple neurons – representing the same information – must exist. Anatomist Mountcastle [4] was the first to observe the micro-column, an arrangement of 110 cortical neurons. The macro-column, is an arrangement of about a thousand micro-columns (about 100 000 neurons) which belong to the same functional unit as exemplified by Nobel laureates Hubel and Wiesel with the orientation columns of the primary visual cortex [5]. The cortical column activity is persistent as long as the corresponding external stimulus is present. On the contrary, the cortical activity is absent when the corresponding stimulus is not present.

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The cortex size (relative to the whole body) is definitely the main anatomical difference between the human species and the other animals. Today's opinion is that the cortex plays a central role in cognition. The larger the cortex (relative to the whole body), the greater the cognitive abilities. The cortex is a flat surface of 2 mm thickness and 0.4 m^2 which neural architecture can be considered uniform (but is not). This surface encompasses three areas: the primary cortex, the secondary cortex and the associative cortex. The primary cortex is directly connected to the various senses (sight, hearing, touch, smell, taste, etc.), the secondary cortex receives inputs from the primary cortex. The associative cortex is supposedly the localization of high level reasoning (*i.e.*, 'associations'). The latter is a very large area since it accounts for 70% of the cortex, which itself accounts for 70% of the brain. The associative cortex accounts therefore for about 50% of the brain volume (and neurons). The cortex functionality appears to be cut into small areas: the cortical maps (Fig. 3).

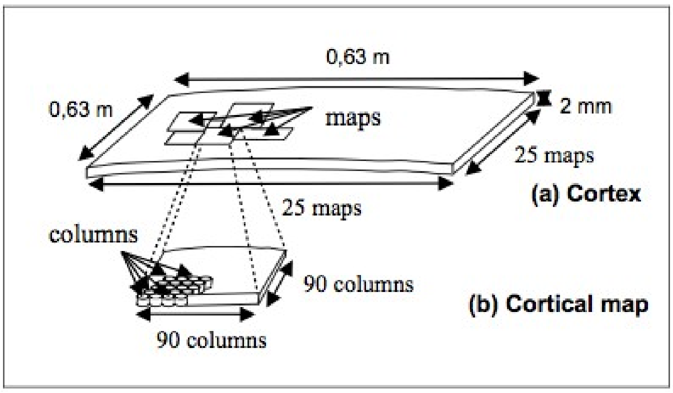

Figure 3. The cortex : a set of several hundreds of cortical maps.

A cortical map is a functional structure encompassing several thousands of cortical columns. The function of such maps is to build topographic (*i.e.*, organized and localized) representations of the input stimulii. The organization is such that similar inputs activate either the same cortical column or neighboring columns. Also, the more frequent the stimulus, the greater the number of cortical columns involved. Seldom stimulus are not associated to the activity of a specific column, less seldom stimulus may activate a column (and share this activation with other similar stimulii) and very frequent stimulii definitively activate a specific column.

Today, about 80 cortical maps are known in the primary and secondary cortex [6]. The functionality of the maps belonging to the associative cortex are more difficult to ascertain – because of the high level of integration of the coded (and represented) information. However, a brain injury called agnosia ('loss of ability to recognize') provides a few more dozens candidates for the functionality of maps belonging to the associative cortex. It is supposed that each symptom is associated to the loss of a specific area of the brain. For example, in the “integrative agnosia”, one has the ability to recognize elements of something but yet is unable to integrate these elements together into comprehensible perceptual wholes – which let us suppose that a least one (or several) map exists that is involved in integrating separated elements into a whole object. The same applies to: Alexia, Akinetopsia, Alexithymia, Amusia, Anosognosia, Apperceptive agnosia, Apraxia, Associative agnosia, Auditory agnosia, Autotopagnosia, Color agnosia, Cortical deafness, Finger agnosia, Form agnosia, Integrative agnosia, etc.

Another interesting fact is the remarkable recovery often observed after cerebrovascular accident (CVA). Patients suffering from brain stroke may for example loss a specific cognitive ability and learn it again. Since the neurons belonging to the damaged brain area are dead, this means that new neurons (respectively to this functionality, not newborn since there is very few neurogenesis in the brain) have to take over. This is a good description of how neuroplasticity works and a good argument towards the fact that the matching between cortical localizations and cognitive functions is a lousy one.

An additional fact demonstrating the lousy connection between localization and function (at the cortical level) is related to the existence of multiple drugs (with different active principles) targeting the same brain disorder, such as depression. In this case, antidepressants are without effect with about one person out of three, and little more efficiency than a placebo [7]. The same symptoms (*i.e.,* brain functions) are seemingly implemented by different kinds of neurons (using different neurotransmitters). Neuroplasticity is again at work allowing various neuron implementations of the “same” cognitive function.

In conclusion, cortical maps seem to be ubiquitous in the cortex (which accounts for 70% of the brain, and is the part definitively associated to cognition) and exhibit all the required 'plasticity' that one could expect from a brain component. A cortical map is a set of thousands of cortical columns, each a set of about 100 000 neurons. Thanks to this huge number of neurons, a cortical column exhibits persistent activity during durations of the order of magnitude of cognitive processes. Also, the matching between input stimulus and column activity advocates a localized processing of information by the cortex. All these facts justify in our eyes the opinion that the natural level of abstraction of cognitive processes is the cortical maps. Therefore, the cortical columns should be considered as the building blocks of any tentative to implement 'neurally inspired' cognition.

4. Discussion

4.1. Cortical maps are successful

Model of cortical maps have been firstly proposed by Kohonen in 1977 [8]. As a token to its inventor, this model is often named a "Kohonen map" (it is also named a "self-organizing map", SOM). Coiton [9] reported the first application of a Kohonen map to robotics (an arm manipulator learning to reach and follow by trial and error) as early as 1991. Kohonen maps provide the most efficient implementation tool for reinforcement learning, an extensively used paradigm in robot learning[10][11]. Today, Kohonen maps have became a very versatile and efficient tool, subject to more than four thousand scientific papers [12]. However, there is a restriction: each time, only a single map is used. What would be the power of several maps working in synergy? A first step in this direction is demonstrated by the instantaneous building (through the use of two Kohonen maps) of any behavior for a mobile robot [13]. Following this seminal work, we have proposed a hierarchical model (fig. 4) of the cortical organization, using cortical maps as the building blocks. This model is known as the Theory of neural Cognition [14].

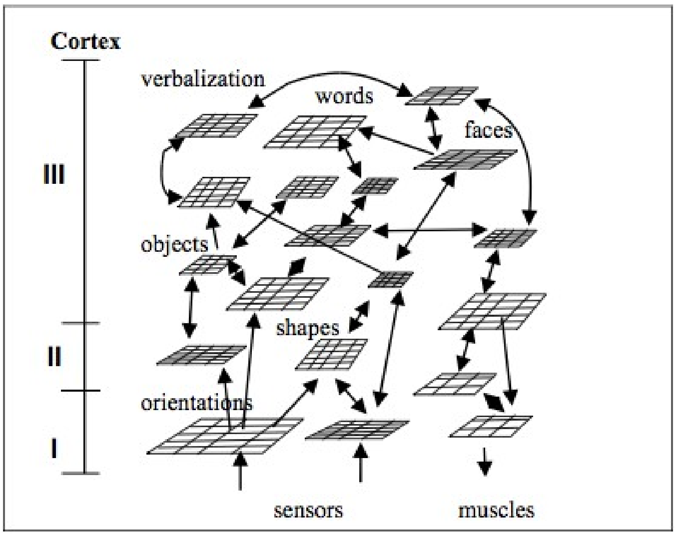

Figure 4. *A hierarchy of cortical maps accounts for the primary (I), secondary (II) and associative (III) cortex.*

4.2. Cortical column unit reduces the complexity

Instead of dealing with models of the brain implying 500 billions of neurons, tentative to achieve (human) cognition should look for models of brain implying only 5 millions of cortical columns (100 000 times less units). This is quite a huge reduction in complexity of the models and in the requirement in computing power.

The computing requirement of a cortical column-based model of the cortex is only 500 GFLOPS (about 10 laptops of 2012, and 'normally' just one laptop by 2016). Such model involves about 600 cortical maps of about 8 000 cortical columns (grid of 90 x 90 columns). The average number of connections per neuron in the brain is estimated to between 1 000 and 10 000, but a given neuron is connected to just a few other neurons (the connection between two neurons involves not one, but many synapses). Therefore, we make the hypothesis that each cortical column is connected to no more than 1 000 other columns. If we assume a maximal frequency of 100 Hz and a 10% update of the cortical columns per cycle, and 10 operations per synapse or column update, then the computing resource required is:

$$5\ 10^6 \text{ x } 1\ 000 \text{ x } 100 / 10 \text{ x } 10 = 500 \text{ GFLOPS}$$

5. Conclusion

Today's failure in implementing artificial cognition is no more due to unreachable computing requirements, but to our inability to envisage the cognitive processing. It follows that today's theories are definitely out of focus, as certainly are the main stream research on cognitive neurosciences. At right angle to existing theories, we propose the Theory of neural Cognition (TnC) which states that the brain does not process information but just represents information ; that consciousness, intelligence and free-will are illusions (as advocates by the eliminativist materialism philosophical position [15]). The TnC models the cognitive processing using cortical maps and cortical columns as the building blocks of cognition.

The TnC explains how every one of the cognitive processes is implemented, and also proposes neural bases for all brain diseases. If we follow the TnC blueprint, artificial cognition may be achieved quite rapidly, at a fraction of the envisaged costs.

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