REPLY TO “COMMENTS ON AUR’S FROM NEUROELECTRODYYNAMICS TO THINKING MACHINES’’

Dorian Aur

1Dept. of Comparative Medicine, Stanford University, Palo Alto, CA

Abstract: The paper [1] relates the general failure to build intelligent thinking machines to reductionist models and suggests a change in paradigm regarding the brain analogy. With the main focus on temporal patterns, the spike timing dogma (STD) has neglected important forms of computation which do occur inside neurons.

Keywords: biological neuron, information processing, spike directivity, nanoneuroscience, neuroelectrodynamics

Intraneuronal information processing at the sub-cellular level is critically important to generate cognitive functions [2]-[8]. We are pleased to see that Gomez-Ramirez has well perceived the relationship between molecular signaling and ‘neural code’ in [1]. Indeed, many scientists tried to explain the variability of temporal patterns based on changes that occur at a molecular or genetic level [9], [10] however, only few have understood that information processing at the sub-cellular level represents itself the ‘neural code’. Any realistic model of computation has to show how information is transferred, processed, deleted and integrated in the brain. Since ‘cognitive’ computation cannot be reduced to information communication between neurons, critical comments in [11] fall short. However, I appreciate Gomez-Ramirez’s comments [11] in response to my paper [1] and the opportunity to elaborate on these ideas further here.

The neuroelectrodynamic model challenges the reductionist philosophy and shows that current models of computation, including the Turing model are a subset of a larger picture. The mathematical model in [1] with equations (Eq-1 –Eq.5) suggest that recorded brain rhythms which sustain the ‘neural code’ and cognitive functions are physically built up from a sub-cellular level through electrical interaction and regulated from a genetic level. Therefore, these five equations provide just a basic model of regulated interactions as has been already stated in [1].

Why do neuroelectrodynamics (NED) criticize the temporal computing machine? The frequency of action potentials (APs) generated by neurons is correlated with different events; however, it does not mean that such events are ‘encoded’ in the brain using the firing rate or any other ‘temporal code’. Unfortunately, too many took for granted Adrian’s observations and hypothesized that neurons behave as metronomes. Lord Adrian can be easily excused since in the 1920s the brain research was in the early stages of paradigm development, there was no theoretical knowledge about computation or complex molecular signaling and no difference between information communication and computation. Lord Adrian and many leading pioneers including Sir

1 To whom correspondence should be addressed. E-mail: DorianAur@gmail.com
Alan Hodgkin could not envision that: (i) The transient electrical activity and temporal patterns cannot ‘hold’ fragments of information; (ii) Our memories need a more stable, non-volatile support at a molecular level (e.g. proteins); (iii) Simple cells have specialized into neurons, that are densely packed and generate electric events at different scales to integrate information in the brain [12]. Therefore, as a whole, the entire brain is the ‘computing’ machine.

Indeed, every model is able to characterize only a few properties of real physical phenomena; important is to understand what needs to be modeled and then in case of complex phenomena to use a systemic approach. We didn’t learn how to fly by copying the morphology of birds feathers; we had to understand the physical principle of winged flight. The inconvenient truth is that in the last sixty years we didn’t learn how the mind emerges from temporal patterns since the entire framework was attached to a false hypothesis (digital spike). Single-electrode recordings and fast propagation of action potentials were the origins of false observations.

For too many, the study of artificial neural networks has generated the illusion that such development is akin to studying the brain. We have shown that artificial neurons that mimic temporal patterns (spiking neurons, weight type connection) are abstract mathematical models which compress information and do not include fundamental (computational) properties of biological neurons. Therefore, the popular claim that current artificial neurons and neural networks are ‘realistic models’ of their biological counterparts it is not true.

The focus on solving equations is admirable; however, we are more concerned what do these equations describe rather than finding a ‘rigorous’ mathematical solution for some arbitrary equations. As Kolmogorov pointed out “it is not so much important to be rigorous as to be right”. With equations written in [1] we follow theoretical ideas developed by great mathematicians and physicists. Gomez-Ramirez is not aware that integrability is a simplification, like linearity or homogeneity assumptions. The behavior of many natural systems including the brain cannot be well approximated using linear models or satisfy integrability conditions.

Throwing terms from physics regarding ‘open’ brain without having a clear understanding of fundamental aspects is another issue. While neurons can be considered open systems since they share directly matter, energy and information with their surroundings [7] the extension of such physical concept to the entire brain is difficult. The receptors for the senses are in general not located inside the brain and during normal brain function neither matter nor energy is shared in a physical sense with the environment. In addition, thinking or reasoning, the cognitive (conscious) state can be maintained in the absence of external stimuli. The process of thought is not simply driven by external sensory influences and sensory information may not necessarily be used in this process. Therefore, the intact brain is not so physically ‘open’ to significantly leak energy, matter or information during thinking or reasoning.

The explanation is simple; it doesn’t involve the ‘open’ brain and was put forward in neuroelectrodynamics. The brain (the ‘thinking machine’) has previously accumulated and stored information inside the biological substrate. Since our memories have a non-volatile support at a molecular level inside neurons, the generated electrical interactions
(e.g. action potentials) dynamically ‘read’ and integrate the required information in the brain. **The thinking machine does not solely rely on sensorial information. This is a major qualitative change of paradigm introduced by the new explanatory approach.** The model of regulated (electric) interactions represents a more powerful framework for information integration than the one revealed by STD.

In addition, George-Ramirez does not fully grasp the systemic approach. Aspects related to metabolic processes, the effect of neurotransmitters and molecular computations (proteins synthesis, transcriptional-translational processes, enzymatic reactions) are included in the other two interacting loops represented in Fig 6, in[1], for details see also [7]. That’s the level where dissipative structures can be correctly defined in terms of Prigogine’s formal concept of self-organization. These changes in the organization that occur at a molecular (sub-cellular) level reshape charge densities within biological substrate and can be modeled as interaction terms in the Hamiltonian of the system. The transient electric events (e.g. action potentials) integrate existential information from molecular structures (e.g. proteins) on a system level. Importantly, the entire neurochemistry and metabolic pathways are required to maintain and regulate the fundamental process of electrical interaction in the brain. The systemic approach in neuroelectrodynamics makes the ‘whole’ from the interaction of the parts. **This is a more substantial paradigmatic shift and the neuroelectrodynamic model becomes an integral part of systems biology.** Having everything in a single loop (e.g. temporal coding) would indeed follow a reductionist philosophy.

Inevitably, in science, any dogmatic view which fails to provide good explanations disappears sooner or later. The vagaries of observations of neural ‘digital’ events on a millisecond time scale and statistical method of thinking didn’t really bring us any closer to the secrets of information processing in the brain. **Our convenience of the digital action potential is our mistake** which has artificially separated electrical events (e.g. APs) from molecular signaling [1] [13]- [15]. This simple observation of meaningful spatial modulation of APs [3][6] has a powerful far-reaching impact in neuroscience, neurology and computer science. Temporal patterns indicate solely when electrical events occur in neurons which partially characterize any electric event (e.g. do not tell what information was processed or electrically communicated). Therefore, the entire framework, the analysis of various time scales (firing rate, ISI, spike timing dependent plasticity) represent just a small part of information needed to characterize electrical communication and not the entire process of computation.

Since memories are stored in non-volatile structures, in proteins [17] then spatial modulation of spikes (see spike directivity) relates molecular computations with information transmitted during AP generation [15]. The similitude between APs and digital signals is irrelevant in terms of information processing. Both events may show similar shapes, however, **the intrinsic nature of computation is completely different.** Adding spikes or computing the firing rate to analyze behavioral semantics [6] or object recognition [3] **incorrectly simplifies** the ‘neural code’. Therefore, theoretical constructs regarding Bayes theorem, nonlinear dynamics, have no real value in understanding how information is processed if they are attached to a false hypothesis (digital spike). In fact, many controversies, contradictions (e.g. myths, concept cells, grandmother cells) are
generated by the ‘most fundamental idea’ of temporal coding [7]. Since **temporal patterns do not provide a reliable approximation of computations that occur within neurons** [1][15], then the temporal computing machine represents an obsolete model.

In addition, Gomez-Ramirez has failed to understand that the **process of computation in the brain emerges from physical interaction**, not from resulting dissipation when information can be deleted (see the Landauer’s principle [7][18]). Given physical implementation, an energy cost is unavoidable; however, the process of dissipation which occurs in many other systems **is not a condition to generate semantics or cognitive abilities**. Since fragments of information are stored within molecular structure (proteins) in neurons a minimalist model of ‘access to memory’ to ‘read’ information through physical interaction is required. Hamiltonian models can well approximate physical interactions.

The fundamental principle of computation in the brain is based on specific interactions. The elegant simplicity of controlling physical interaction in the brain and neurons is meaning-making [3][6]. In [1] we tried to find a simple, yet a non-trivial model to describe the non-mysterious nature of such interactions. The Hamiltonian structure in [1] extended to infinite dimension case models the interaction of electric field with charges, resulting resonant regimes or chaotic dynamics. These interactions intrinsically exhibit many features such as parallelism, fuzziness and fractional dynamics [20]. The Hamiltonian formalism is not limited to classical mechanics. **From quantum (molecular dynamics) to classical systems (celestial mechanics), Hamiltonian models can approximate nonlinear interactions.** Feynman has presented the first convincing Hamiltonian framework for physical (quantum) computation few decades ago [19]. The approximation in the action-angle form (Eq.2) generates extreme examples of the kind of behavior the brain can exhibit. There’s no need to solve “6M1010 equations” to understand that complex brain rhythms, resonant regimes (Eq.3) or generated chaotic dynamics (Eq. 4) represent this kind of ‘solution’. The AP itself is a complex process of interaction where resonant regimes are present and can be evidenced within generated electrical patterns [2][3][7].

The neuroelectrodynamic model was tested by experiment; however the falsity of observations still remains an issue in neuroscience. The stereotyped action potential (AP) is just an appearance. Since **single-electrode recordings are inadequate to capture spatial propagation of a spike, such fast modulation that occurs during AP generation (1ms) is completely ignored in current recordings** [3][7]. Occasionally, few electrophysiologists have observed changes in APs waveforms. They recognized these changes, unfortunately when they tried to understand what was really behind this phenomenon, they failed almost completely [16] (see explanations in [2]-[7]). The stereotyped appearance of spikes is still deceiving and is similar to the belief of a fixed, flat, Earth which was a popular myth 500 years ago. Experimental data show patterns during action potential generation [2][3][7] which point to a sub-cellular level of information processing. The all-or-none action potentials are fast events; however they are not digital signals [21]. The meaningful change of spike directivity [6]contains the basic mystery of neuroelectrodynamics. This ‘faithful conduction’ [21] during APs represents a complex process of interaction when information is electrically exchanged
between molecular structures (proteins) which store fragments of information and the generated electric flux which carries information. Every neuron 'speaks' in less than a millisecond during action potential generation. The action potentials are the meaningful 'words'.

**Electrical interactions that occur within neurons, inside the brain cannot be approximated by temporal patterns** [3][7]. A comparative statistical analysis shows that electrical patterns approximated by spike directivity convey far more information regarding presented images than the firing rate or interspike intervals [3]. This experimental result proves that temporal patterns don’t provide a reliable approximation of electrical interactions. Importantly, the semantics are hidden in spatial modulation of action potentials which shows that the **semantics are built and integrated into the cognitive level** [3][6] through electrical interactions [7][15]. The result proves that ‘cognitive maps’ have their origins in interactions that occur inside many neurons which ‘fire together’ to electrically integrate information in the brain (see Fig. 5 in [3]). All these experimental results confirm previous theoretical work [22][8] and explain why a digital approximation of APs completely changes the nature of computation that leads to an incomplete model [23]. With no associated semantics, the entire algorithmic construct of temporal computing machine is meaningless.

While ‘weak’ interactions between neurons may be algorithmically approximated, ‘strong’ interactions that occur inside neurons during AP generation remained unmodeled. In a Turing model, macromolecular assemblies (proteins) which store fragments of information can represent the ‘tape’ and the electric (ionic) flow can be the ‘head’ which dynamically ‘reads’ or ‘writes’ information inside neurons [7][15]. However, the relevance of Turing model is questioned even in case of present-day computing [24][25]. Since the super-Turing computing power of the brain has its origins in these ‘strong’ interactions that occur inside neurons, current models have missed the most important part. We are not concerned about ‘small imperfections’ (e.g. dissipation) virtually, included references and any undergraduate textbook explain introductory topics on Hamiltonian mechanics (e.g. integrability). Gomez Ramirez is totally unaware that in the last sixty years the studies of Hamiltonian systems have moved further to include the physics interesting points, which are beyond complete integrability. With equations written in [1] we follow theoretical ideas developed by great mathematicians and physicists. For details see references in [1].

While previous models have attempted to represent Hamiltonians using Turing machines [26] the paper [1]shows that the Hamiltonian model of interaction can represent itself a far more powerful model of computation. In this sense, the new framework of computation using interaction is universal in nature and provides a more general description of computation than the formal Turing model. In other words God was unaware of Turing's work and has put forward a better model for physical computation in the brain. Once this chronic failure generated by temporal computing machine is accepted, further progress is possible. We have to admit that up today consciousness didn’t emerge from STD or any other algorithmic model. Turing made an important step forward; however, there is no need to limit physical models of computation to Turing
models. The entire solution regarding consciousness lies in ‘strong’ interactions developed within neurons. The process of computation by physical interaction [15] generates itself a more powerful model of computation with a super-Turing behavior. Since fragments of information are stored inside neurons, then the regulated electrical interactions can bring information together; give rise to memory based experience which provides the basis of cognition and consciousness [7].

Indeed, the theory of mind and consciousness can have a computational framework [27] however, it is a non-algorithmic one. Even the ‘non-computational’ theory of consciousness presented by Sir Roger Penrose [28] becomes ‘computational’ within the new description. Once we have the right theory [7] the unobservable mind [29] turns out to be observable from the smallest level. Remarkable, similar views regarding physical processes are lately shared by Terrence Deacon [30] and confirm our approach to understand the brain.

The neuroelectrodynamic model provides a new computational theory of mind, brings back the strength of physical laws which show how information is transferred, processed deleted or integrated in the brain [1][7]. There is no need to develop temporal coding frameworks to understand how the mind dynamically emerges from the interaction of matter. Physical models can explain better these phenomena. The new framework NED, provides clear explanations for many unsolved brain mysteries (e.g. mirror neurons, phantom limb, sparse coding), generated neurological disorders (e.g. seizure generation in epilepsy [31]) or even for the ‘natural’ variation of hypothesized neural code [9]. At least three regulatory interconnected systems (see Fig.6 in [1]) maintain a direct relationship between biological substrate and controlled brain rhythms which underlie cognitive processes and consciousness.

Without a doubt, as presented today ‘neural’ computation describes a model of communication between neurons rather the required physical model of computation. A common mix-up is to claim that ‘spikes convey information’, then hypothesize, they are digital events and limit the entire model to a digital communication of temporal patterns. The simple process of communication (either modulated or not) does not describe the entire process of computation. At least information storage, information integration has to be included in the model and related to changes that occur in biological substrate (e.g. proteins), see details in [1][7]. Otherwise, all temporal patterns disappear into ‘thin air’.

Indeed, “physical realization” needs to be considered and the simplicity underlying the physics of interaction is highlighted in neuroelectrodynamics [7]. We are pleased to see that Gomez-Ramirez starts to understand that information is not stored into ‘thin air’ (e.g. temporal patterns) and that fragments of information can be physically deleted in the brain. In fact this is the first compelling proof that Gomez-Ramirez begins to understand and learn neuroelectrodynamics. Does spike timing dogma or ‘classical’ artificial neural networks explain these processes which occur in the real brain? No, they have remained too ‘artificial’. In the last sixty years, only few models have included a relationship with biological substrate (see references in[1][7]).
In fact, STD can be seen as a particular case of neuroelectrodynamics, an approximation when APs are digital events and neurons behave as metronomes. One could try to record, perform statistics or mimic the occurrence of temporal patterns for a lifetime without learning anything about what they really represent. The spike timing dogma has artificially amplified the gap between cognitive processes and physical realm. Given the focus on the boundaries between biological grounds and cognitive computation, general topics related to Hamiltonian dynamics (e.g. integrability) remain the Quixotic ‘windmills’ believed to be the malicious giants. We have shown that George-Ramirez is confused about physical and mathematical concepts and it is time to ask ourselves; where are the real conceptual pitfalls? After all, George-Ramirez doesn’t have an adequate understanding of the nature of the problem presented in [1]. The transition from temporal coding dogma to neuroelectrodynamics is not easy and we expect more resistance from well-known research since only few have understood that cognitive processes and emerging consciousness are grounded in continuous, regulated dynamics of physical interactions in the brain.

References


