New Paradigms for Information Processing: A New Approach to Dendritic Computation. Quantum Chemistry Models for Cognition

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Abstract

A model of dendritic computation based on active zones is first described and is used in a Quantum Chemistry model for purely cognitive or else cognitive-affective or cognitive-motor psychophysiological processes.

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1 Introduction

The dendritic computational process was studied by our group in a passive perspective. It was then evident that a likely representation, from a new physiologic viewpoint of complex interactive processes was necessary. For instance the function of convolution and correlation were impossible to obtain respecting well known neurophysiological parameters. Our present work concerns a putative hybrid mechanism with two main components: one logical and another analogical. And a third component with discrete properties: the calcium spike potentials in dendritic spines.

The logical function of implication $F(X,Y)=X \supset Y$ which is defined in extenso by

$$F(X,Y) = X.Y + \overline{X}.Y + \overline{X}.\overline{Y} \qquad (1)$$

will be used as a determinant of ostensive discrete facilitation of computations simultaneously logical and analogical. It is a fact that using both these elementary functions can be obtained results in an objective advantage.

To represent multiplication and division it is enough to use algorithms of iterative sums and subtractions, respectively.

Then in a terminal branch multiplication or its inverse factor being indicated by the number of interactions then in a final dendritic branch the result of either multiplication or division is indicated by the number interactions.

The relationship between postsynaptic potential and trains of spikes is defined by

$$f(t) = c_1 V_m(t) + c_2 \frac{\Delta V_m(t)}{\Delta t} \tag{2}$$

with f(t)=0 for $t<t_0$ or $t>t_f$.

The amplitude of the calcium spike diminishes exponentially during spike propagation while excitation propagates along the dendritic tree according with one of the four Rall conditions: a) infinite cable with open end; b) finite cable with closed end for the case of transient potentials; c) finite cable with closed end for the case of steady potentials; d) time and space propagation of transient potentials.

When the excitation arrives at active zones with an exponential decay with amplitude enough to reach the threshold of voltage sensitive calcium channels (which are also sensitive to gluthamate) the full amplitude of the spike potential is restored.

This mechanism is similar to the one observed in the Ranvier nodes in mielinated axons. The scale factor is introduced by the simultaneously voltage and the neurotransmitter sensitive NMDA channels while AMPA channels play only an auxiliary role.

The calcium voltage sensitive channels have a role in the regeneration into full amplitude of signals that have suffered an exponential decay along the trajectory of propagation. It is supposed that the initial postsynaptic potential generates a train of calcium spikes sufficient to regenerate the original post-synaptic potential and its decay.

To implement the computation of the correlation of two input signals, f_1(t) and f_2(t), which in discrete domain is defined by

$$\Phi(f_1, f_2, \tau) = \frac{T}{2N^2} \sum_{i=-N}^{N} f_1(iT/N) f_2(iT/N + \tau) \tag{3}$$

two dendritic branches are enough and on the other end the admission of the hypothesis that exists dendrodendritic facilitation which imply both input and output synapses as they exist in invertebrates and in the SNS of some mammals.

The production of calcium spikes is due to the activation of sensitive voltage calcium channels, related to NMDA and AMPA receptors, that make use of the convergence of Glutamate action and depolarisation provoked by postsynaptic dendritic potentials.

The analytic expression of the convolution of two input signals, f_1(t) and f_2(t), in the discrete domain is defined by

$$\Theta(f_1, f_2, \tau) = \frac{T}{2N^2} \sum_{i=-N}^{N} f_1(iT/N) f_2(\tau - iT/N) \tag{4}$$

2 Elementary Components of Dendritic Computation

Membrane voltage is typically

$$V_m(t) = V_{ion}\, t\, e^{-\lambda_1 t} \tag{5}$$

which has a maximum of $V_{ion}/(\lambda_1 e)$ at $t=1/\lambda_1$, and then decays exponentially and the frequency of chain spike production in the dendritic spines depends on the absolute value of excitation and on its rate of change.

Hebb's learning algorithm may be implemented in a similar manner.

When arrived to the active zone the excitation with its exponential decay is regenerated by the activation of calcium voltage sensitive channels.

This mechanism is analogous to the one observed in the nodes of Ranvier in myelinated axons. The scale effect of the activation of NMDA receptors not only equalizes the class of states of excitation that arrives to the axonal hillock, but will have a similar effect on the class of states of excitation that retropropagate to the dendritic closed ends of apical dendritic ramifications that receive postsynaptic excitation from predecessor neurons.

This way the excitation retropropagated from active zones till the apical extremities of dendritic ramifications after being regenerated in the active zones placed on conventional predecessor zones will facilitate postsynaptic excitation produced by a predecessor neuron and it is even capable of liberating retrograde neurotransmitters such as NO and CO_2.

If we consider cognitive processors which imply complex operations over relationships as well as the use of individuals and abstract categories and the convergence of multi sensory associative information requires the construction of complex structures. We will use in what follows the paradigms of multi global chemical reactions and the Quantum theory of Valence.

3 Neuronal and Computational Implementation: The Dendro-Dendritic Network Model

3.1 Neuronal Implementation: The Dendrodendritic Network Model

If we consider neural architectures, dendro-dendritic networks possess the remarkable characteristic of allowing both forward and backward propagation. The complex geometry of these networks permits back propagation of action potentials generated at the axon hillock. Ultimately when such potentials attain fine dendritic ramifications they can eventually fade out. When this is not the case such potentials can oscilate forward and backward in a single dendritic tree or in dendrodendritic networks which implement local computations.

Although dendro-dendritic networks are extremely dense anatomical structures with interspersed almost reticulate structures linked by multiple synapses, they may be

thought of as an ensemble of computational compartments. Let us consider the case in which information arrives to the dendritic neuropile through axo-dendritic and dendro-dendritic synapses.

If we attribute to each neuronal cell body a set of characteristic dendritic oscillators or dendro-dendritic closed loops we may consider each such set as an ensemble of oscillators with characteristic frequencies. We assume that complex information processing is performed by each neuron due to its oscillators and closed loops. Similar functions are served by identical sets of oscillators and closed loops and distinct functions are implemented by different sets of oscillators and closed loops, A, B,..., Z.

If the same information arrives to an ensemble of distinct sets of closed loops each one performing the analysis and processing of the incoming information from a distinct viewpoint, we may assert that an input vector {Y} (coming from the output of a predecessor structure) activates distinct sets A, B, ..., Z of dendritic oscillators and dendro-dendritic closed loop operators.

From the viewpoint of our analysis it may be considered that 'compounds' Ay, By,..., Zy have been formed and the corresponding information will be transmitted by neuronal cell bodies at a distance to decision making neurons responsible for the generation of coordinated patterns of action. A, B, ..., Z, are closed loop operators or oscillators; $y \in \{Y\}$ are a subset of ordered components of {Y} with dimension(y)≤dimension({Y}).

3.2 Anastomotic Computation

One way of understanding anastomotic computation is to consider a convolution matrix of dimension **k** x **k** which acts through a inner product over a data matrix of the same dimension. It is furthermore supposed that the convolution weighing matrix is constant while data do vary.

This is a way to understand preprocessing of data along an active set of information transmission and computational parallel and interactive dendritic lines with forward and backward propagation.

Furthermore chemical paradigms allow the creation of systems in which the convolution weighing components are transmitted along together with the data matrix in a computational dynamic flow.

A further generalisation leads to the concept of a dynamic convolution with variable coefficients. This last non-linear paradigm may also contribute to understand the way in which operative instructions are transmitted at a distance and are transformed in characteristic and distinct ways by the neurons that receive them.

Besides the usual concept of data transmission between computational stations we have here a paradigm for the transmission of computational instructions which produce a local transformation at each computational station which receives them.

This computational model is likely to exist in the peripheral and Central Nervous System. The chemical metaphor closer to it is the model of plug flow reactors.

4 Towards an Homeomorphism of Isolobal Analogy

One of the main theories, which explain chemical reactions, is the molecular orbital theory. In organic molecules it is possible to substitute carbon atoms by metallic heteroelements if we use metal ligands and we create fragments with the adequate symmetry, level of energy and adequate valence structure in the bounding surface of the new component fragments.

The valence frontiers of both the organic fraction and the metallic complex do not need more than an approximate match. Hoffmann used a transformed Mendeleiff table to characterise the orbital structure of each element.

These two fragments are called *isolobal* if the number, symmetry properties, approximate energy and shape of the frontier orbital and the number of electrons in them are similar (Hoffmann, 1982).

With the support of this data and using considerations issued from group theory and Quantum Mechanics Perturbation Theory he was able to make exact predictions about sets of equivalent component fragments that matched and reacted with complex organic molecules.

Here we find a paradigm for classes of equivalence of organometallic compounds.

Returning to the proposed homeomorphism between dendritic oscillators and dendro-dendritic closed loops on one hand and orbitals on the other, we can define interaction surfaces that are composed by dendritic computational compartments that are attached to a complex set of neural bodies.

The valence sites are identified as computational compartments of dendritic oscillators and dendro-dendritic closed loops which include input and output synapses. These synapses contribute to an interaction surface through which this computational assembly can be linked to distinct assemblies. This metaphor is convenient to represent some characteristics of cognitive and emotional processes.

Namely we are thinking about the knowledge that cognitive operators concerning lower level sensory and motor processes and memory representations. Emotional memory and sensory information may impinge on a single cognitive Valence surface and became assembled as a temporarily stable operation compound.

The inquiry about what is occurring at a sensory and motor level in a transaction with the environment may be compared to the successive linkage of a matrix of organic complex molecule to distinct equivalent isolobal metallic fragments.

A first characteristic of this class of equivalence is that it may represent a concept in extenso. On the other hand as this organometallic complexes are very unstable they may contribute to represent a sequence of inquiry operations in which distinct attributes of a concept are successively scanned.

All of them remain available to a further inquiry but only those which form stable complexes give rise to a conscious experience.

The correlate for the conscious character of cognition may be found in the way microscopic interactions generate the emergence of macroscopic qualities in some particular neuronal structures. Let us remember the role attributed by Koch and Crick to

area V4 in visual awareness in the case of Necker cubes or alternating visual gratings. Comparative neuroanatomy and neurophysiology help to specify as a further requirement that consciousness must be related to secondary and terciary multisensory and idiomotor areas of the Brain in Primates and Man.

Ultimately the Quantum valence bounding surfaces may be considered putatively as a possible correlate for the type of binding of distinct sources of information which are involved in complex cognitions, emotions and motor plans.

The resemblance between two neurons assemblies together with their characteristic dendro-dendritic closed loops that can participate in neural connections allows them to generate a complex and self-organised structure. A modular architecture is attained that on one hand emulates knowledge representation by a frequency code and on the other hand reduces the number of distinct components by the *chemical* operation of dislocation and binding by Valence Bonds of frequency operators. This functional architecture reduces the number of components necessary for multiple successive representations, anihilating the counter argument of Marcus (2001). Finally, this analogy also provides a hypothetical framework to understand abstract cross-modal representations.

5 Conclusions

Dendritic computation may be characterized at least as possessing two levels of complexity. At a first level we may define discrete signal processing with the participation of NMDA channels in dendritic spines with voltage gated calcium channels which are also dependent on voltage drop inside the cell and active zones may play a role in signal regeneration after exponential decay due to passive conduction along larger extensions of passive dendritic membrane. Two way computations inside the dendritic tree and reverse excitation transmission may generate oscillations which implement dendritic computations.

If we endow this computational architecture admitting a putative Quantum Chemistry Valence Homeomorphism we attain a level of complexity in knowledge representation and cognitive operations that imply the emergence of macro qualities from micro structures.

References

Barahona da Fonseca I., Barahona da Fonseca J. and Simões da Fonseca J. (1995). Dendritic Computation in the Brain. From Natural to Artificial Neural Computation. Edited by J. Mira y Mira and F. Sandoval, Springer-Verlag, pp 260-267.

Barahona da Fonseca J., Barahona da Fonseca I. and Simões da Fonseca J. (1995). Visual Information Processing from the Viewpoint of Symbolic Operations. From Natural to Artificial Neural Computation. Edited by J. Mira y Mira and F. Sandoval, Springer-Verlag, pp. 253-260.

Blakemore C. (1974). Development Factors in the Formation of Feature Extracting Neurons. Neuroscience Third Research Program, 105-113.

Blakemore C. and Cooper J. F. (1970). Development of the Brain Depends on the Visual Environment. Nature 228, 477-478.

Hoffmann R. (1982). Building Bridges Between Inorganic and Organic Chemistry. Angewandte Chemie, Vol. 21, N° 10, 711-724.

Hubel D.H., Wiesel T.N. (1965). Receptive Fields and Functional Architecture in two Non-Striate Visual Areas (18 and 19) of the Cat. J. Neurophysiol.

Lettvin, J. Y., Maturana, H. R., McCulloch, W. S., Pitts, W. H. (1959). What the Frog's Eye Tells the Frog's Brain. Proc. Inst. Radio Eng., New York.

Marcus G. F. (2001). The Algebraic Mind: Integrating Connectionism and Cognitive Science. MIT Press, Cambridge, Massachusetts.

Simões da Fonseca J., Barahona da Fonseca J. and Barahona da Fonseca I. (1996). Cognitive Processes-Representation of Events and Operations from the Viewpoint of Dendritic Computation. Brain Processes, Theories and Models. Edited by R. Moreno-Díaz and J. Mira Mira. MIT Press, Pp. 173-183.

Tolman E. C (1932). Purposive Behavior in Animals and Men. Century Co., New York.

Tolman E. C. (1938). The Determiners of Behaviour at a Choice Point. Psychol. Rev., 1, 41.