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Associable representations as field of influence for dynamic cognitive processes

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In earlier models, synaptic plasticity forms the basis for cellular signaling underlying learning and memory. However, synaptic computation of learning and memory in the brain remains controversial. In this paper, we discuss ways in which synaptic plasticity remodels subcellular networks by deflecting trajectories in neuronal state-space as regulating patterns for the synthesis of dynamic continuity that form cognitive networks of associable representations through endogenous dendritic coding to consolidate memory.

Keywords: Subcellular networks; dendritic coding; memory consolidation; molecular biophysics; electrical signals; cognitive processes; trajectories; physical theory; electric fields; ionic charge densities.

1. Introduction

The cerebral cortex (neocortex) is an extremely complex structure in a state of continuous activity. The activity is associated with spatiotemporal patterns in neural circuits and their intricate interactions during cognitive function that occur in the cerebral cortex. These dynamic spatiotemporal patterns in neural circuits are transformed into different patterns or become abortive whilst others are not. The substrate of such changes is not just structural occurring at the synapses (Hebb, 1949), but dynamical caused by a postulated “field of influence” (Eccles, 1953). According to Eccles (1990, 1994), cognitive states underlying cognitive processes can produce an integrated subjective experience in which a “field of influence” could account for cortical integration.

Cortical integration occurs over hundreds of thousands of synapses in a few milliseconds producing a “field of influence” between the spatiotemporal patterns. Synaptic integration within a few milliseconds between hundreds of thousands of neurons would be unique since it nonlinearly exerts an effect in some specific way creating a shifting harmony of sub-patterns of neural activity. Furthermore, if the

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spatiotemporal patterns of neural activity are endogenously generated in dendrites then, elucidating the dendritic code cannot be deduced from coherence of local field potentials carried extracellularly in modulating the excitability of neural assembly dynamics (Achimowicz & Bullock, 1993) or from experimental confirmation of synchronous activation of neural assemblies during spiking through measure of brain rhythms at multiple frequencies (see e.g., Benchenane *et al.*, 2010). As such, synapses play an intermediary role in generating such activities.

The integration of the neural patterns and their emergence across multiple brain areas is dependent on the endogenous structures in subcellular networks of cortical dendrites. The dialogue between brain areas is the basis of most cognitive functions and is carried out without reference to spike timing or field potentials in extra-cellular neuroimaging studies. Moreover, such a “field of influence” in the extra-cellular medium [cf., Green & Triffet (1985, 1997)] would not discriminate between spatiotemporal patterns; thus spatiotemporal patterns of cognitive activity would not be uniquely archived. Consequently, a field theory of higher cognitive functions [see e.g., Perlovsky (2006)] would not be suitable. Instead, protein polarization, resulting from the summation of all ionic charge densities on the Debye layers of endogenous structures in subcellular networks of cortical dendrites, could be the postulated “field of influence” of endogenous dendritic coding (see Woolf *et al.*, 2009). This would avoid experimentally untestable claims of field theories proposed by Eccles and others, instead advocate electrical interactions on the Debye layers of endogenous structures in subcellular networks of cortical dendrites within the electrolytic environment for encoding and decoding. All computations are performed by physical interactions through charge dispersion which contributes to ionic current flow in neurons (Aur *et al.*, 2011).

Electrodiffusion of ions as a physicochemical process requires a new electrolytic cable theory based on the earlier work of Green and Triffet (1975; 1982). Such cable modeling can be daunting as it must be electrochemical in the sense of establishing the spatial distribution of ionic concentrations driven by their concentration gradients and by the electric field (cf., Leoneti *et al.*, 1999). Although the Poisson-Nernst-Planck system of equations has been used in the past to investigate electrodiffusion of ions including proteins in terms of electrophoretic waves, such approach is electrochemical rather than electrical and therefore it cannot be reconciled with cable theory like the Hodgkin-Huxley cable analogue. The effects of protein diffusion or electromigration and electrodiffusion of ions acted upon by electrochemical gradients that produce ionic composition changes in the ionic environment can be approximated as charge fluctuations using Maxwell’s equations of electromagnetism relating current, charge density and the electric field. The electrodynamics of cable theory where charge fluctuations along the Debye layer of endogenous structures is approximated as thermal noise and then integrated with the membrane potential has been developed by Poznanski (2010). Such a Maxwellian approach, although not physicochemical as it neglects concentration gradients in the electrolytes can nevertheless heuristically unify action potential propagation

with electrodiffusion. The process underpins an important theoretical understanding of subcellular signalling that is so far missing from other approaches based on biochemical signaling (see Bhalla, 2002).

The earlier views of memory stored by modification to the synaptic efficacies (Filkova & Delay, 1982; Bliss & Collingridge, 1993) as a process of synaptic tagging need to be revised in view of the fact that synapses are junctional sites of transitory events and not stable sites for memories to be permanently stored. Synaptic switches have been postulated for controlling synaptic efficacies such as CaMK II for short-term memory (Miller *et al.*, 2005) and MAPK for long-term memory (Bhalla *et al.*, 2002). Although these electrostatic interactions provide viable mechanisms for changes in synaptic weights as commonly used in artificial neural networks (e.g., Fusi *et al.*, 2005), they are unfeasible substrates for stable memory and therefore, the computation and storing of memories must occur beyond synapses. Indeed, the entire cell is involved in learning, computation and strong memories which has been neglected by all previous models. In particular, there is a consensus on how memory is consolidated at the subcellular level in terms of dynamic spatiotemporal patterns of electrical activity (Priel *et al.*, 2010) distributed over large brain areas in the form of associative representations (Woolf, 1998). Nevertheless, irrespective of the plasticity mechanism or ‘learning rule’ used to encode memory patterns (Abbott & Regeher, 2004) all synaptic loci models depend on symbolic representations for memory consolidation, in contradistinction to modern cognitive science (Spivey, 2007).

2. Trajectories as regulating patterns of dynamic continuity

Dynamic continuity exhibits continuous internal perceptual-cognitive processing whose function is to mediate between sensory stimulation and motor action (Freeman *et al.*, 2011). Dynamic continuity is the integration of various micro-, meso-, and macro-dynamical systems across spatial and temporal scales leading to the formation of neuronal groups or assemblies consisting of many brain networks which themselves consist of many different neuronal networks, comprising many different neural circuits. Each neural circuit consists of a few neurons in which a specific spatiotemporal pattern of electrical interaction canvases these neuronal activations into what is referred to as a neuronal state-space in the language of landscape metaphors for dynamical systems. In this context, dynamic continuity means a continuum of spatiotemporal patterns of neuronal activation, while associable representations are trajectories through neuronal state-space. Experimental findings from acknowledged work on savants indicate that disintegration of these spatiotemporal patterns of neuronal activation can bring about lower-level recall of vast raw sensory information processing at the expense of cognitive functions, such as conceptual thinking (Snyder *et al.*, 2003; Snyder, 2009).

An associable representation is not a neural representation that symbolizes some external object, but a continuous dynamic cognitive process. According to Spivey

(2007), it is a trajectory through neuronal state-space consisting of multiple cognitive states being simultaneously activated in replacement for the traditional notion of static symbolic representation. Moreover, dynamic continuity through neuronal state-space depicts an associable representation that is unique; in other words, it is the trajectory rather than the location in neuronal state-space how the associable representation manifests. This leads to associable representations as trajectories through neuronal state-space innately dependent on dynamic continuity and dispenses with the notion of discrete symbolic processing underlying cognitive processes. However, such conception focused robustly that a continuous configuration of neuronal activities gives rise to dynamic cognitive processes without explaining how.

In conformity with Spivey (2007), a cognitive state underlying a cognitive process involving the firing of thousands of neurons in concert underlies continuity. However, this is somewhat contradictory because both the temporal spiking and the rate spiking are discrete phenomena. This requires cognitive state to be redefined by a “field of influence” in terms of a network (i.e., cognitive network). The continuity in the spatiotemporal dynamics as a “field of influence” means movement from one cognitive network to another. These dynamic events bring about a cognitive state where dynamic continuity traverses a vast number of cognitive networks as it is integrated to form a conceptualization of an associable representation. The uniqueness of each associable representation can be attributed to a specific spatiotemporal pattern of neuronal activity associated to a particular cognitive network in the cortex.

The conceptualization of associable representation cannot be confined to a single cognitive state as it involves trajectories through neuronal state-space. What is a trajectory? It is a flow of information within the “field of influence” and therefore taken to be the regulating patterns of dynamic continuity that form cognitive networks of associable representations. In the language of landscape metaphors for dynamical systems, it is one attractor in neuronal state-space moving to another attractor. The spatiotemporal activity continuously traverses its neuronal state-space finding an attractor to bring that attractor’s actions. The emphasis is on the pathway, not the locations. The evolution is a natural continuously dynamical event that corresponds to a trajectory in neuronal state-space. According to Spivey (2007), there are no discrete regions of neuronal “state-space” in which unchanging symbolic representation (or “look-up” tables as envisaged by Poggio (1990)) could reside. Hence, there is no such thing as a static associable representation. Its form of existence is therefore of a trajectory through neuronal state-space abounding multiple cognitive networks. Cognitive networks are particular trajectories in neuronal state-space that describe those associable representations. Woolf (1998) offers a similar definition for associable representations as sets of functional states linked to cognitive processes confined to cytoarchitectonic modules of the cerebral cortex, hippocampus, and amygdala. They are part of the synaptic signaling mechanisms (event-related phenomena of the brain) that have functional roles in adaptive

behavior. These synaptic connections can control the dynamical flow across the neuronal state-space rendering trajectories into regulating patterns of dynamic continuity that form cognitive networks of associable representations. The challenge is to identify distinct configurations of spatiotemporal activity that triggers associable representations. Such distinct configurations are not differences in neuronal response that can be associated with either temporal coding or rate coding (see Gautrais & Thorpe, 1998).

What the earlier pioneers of neurology referred to as “recollections” as neural representations cannot be physiologically proven. De Charms & Zader (2000) argue that neural representations are successions of brain states arising by consecutive excitations of the brain. These excitations have temporal logic resulting from the structure of the brain. The structure exists in a form of “memory traces” and is actualized by the dynamical processes in the brain. The problem with neural representations is that they rely on stored memory for their interpretations. If the meaning is not intrinsically imbedded, but reflects a dynamical state that has no syntactical representation, then how do existing associable representations remain intact? The non-spatial character of cognitive networks can be explained by the conceptual interpretation of guiding “templates”, without having necessarily spatial discourse. Templates have no spatial association linked to the meaning associated with a neural representation. Templates manifest in subcellular networks guiding the dynamics associated with synaptic and extrasynaptic transmission (Semyanov, 2008) at assemblies of neural networks (i.e., functional collection of neurons in the cerebral cortex) without intrinsically altering the cortical network. In other words, neural representations invoke extant trajectories through neuronal state-space as cognitive networks of associable representations. It can be seen, therefore, that neural representations exist only as associable representations that can be attributed to cognitive processes but not vice-versa. Meaning that there are no pre-existing neural representations or “look-up” tables.

3. Dialectics on dynamic continuity and dynamic connectivity

Dynamic continuity, in the spatiotemporal pattern of activity, is attributed to the electrical interactions that occur within the Debye layers along endogenous structures in subcellular networks of cortical dendrites. The spatiotemporal activity is measured as observed changes in the diffusion potential within the Debye layer that is influenced by synaptic activity. The process plays a fundamental role in depositing the surface charges on the cytoskeletal structure for decoding. Experimental evidence has pointed to cytoskeletal structures having substantial ferroelectric properties and thus can store permanently ionic charge (Woolf *et al.*, 2009). Hence, an associable representation is replicated uniquely by the charge configuration on the cytoskeletal structures imprinted by a dendritic spike. The uniqueness stems from neural circuits continuously involved through feedback in shaping the spatiotemporal activity patterns in the cerebral cortex. On this account, it is possible that the

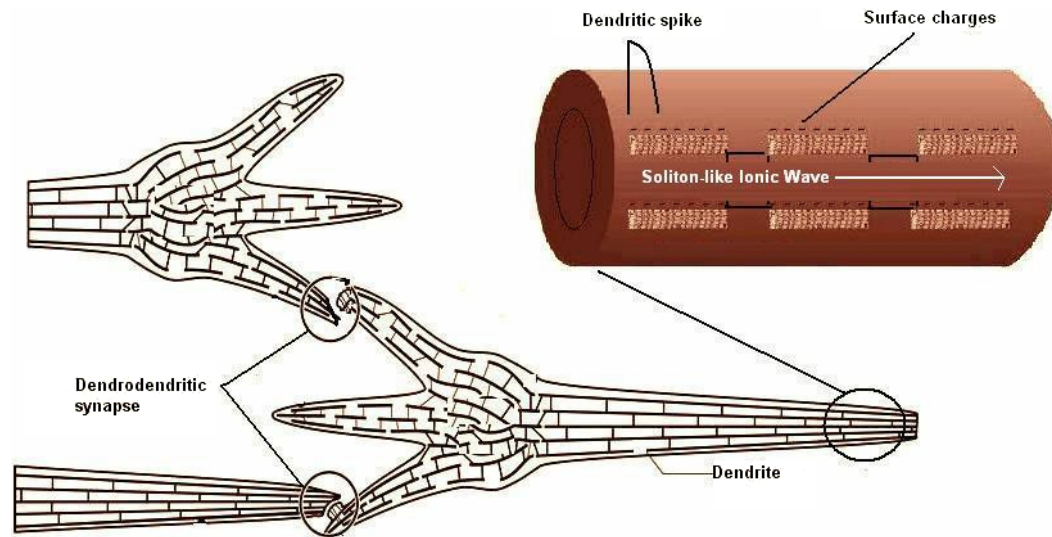


Fig. 1. Schematic diagram illustrating a neural circuit consisting of dendrodendritically coupled neurons. Synaptic transfer allows for the dynamic continuity to manifest when the spatiotemporal pattern is flowing, but also the neuroelectrodynamics is aborted by inactive synapses leading to what is termed dynamic connectivity. Inset is a magnified view of the cortical dendrite showing intracellular membranes of cytoskeletal structures with ionic charge densities on its surfaces. A dendritic spike is hypothesized to provide an imprint for neural encoding, with drifting soliton-like ionic waves scanning the imprint of shielded (or stored) ionic charge densities for neural decoding. Electrolytes have their own characteristic charge and the ionic charge densities depend on position and time. In principle, an unlimited amount of information can be processed depending on the ionic charge configurations that can be stored along cytoskeletal structures with the semblance of ferroelectric capacitors. Adapted from Hamerhoff (2007).

existing pathway is erased due to synaptic connectivity loss and not due to charge configurations on endogenous structure being overwritten (see Fig. 1).

Cognitive networks of associative representation are reflected upon as regulating patterns of dynamic continuity. When these spatiotemporal patterns of activity in-between distinct cognitive networks (or large-scale patterns of temporal correlations generated by the dynamics of neural connections) are altered by changes in synaptic connectivity, this is what is loosely referred to in the literature as dynamic connectivity (see Breakspear, 2004; Jirsa & McIntosh, 2007). A change to synaptic efficiency and hence synaptic connectivity brings about dynamic connectivity. The term “dynamic connectivity” refers to several different and interrelated aspects of brain connectivity: functional connectivity and effective connectivity, but there is no consensus what dynamical connectivity in the cortex represents (Horwitz, 2003).

Cognitive networks are investigated in the context of dynamic connectivity. It has been proposed that both cortical segregation and cortical integration are in unison where the cortical segregation and cortical integration results in information that is simultaneously highly diversified yet highly integrated, thus creating patterns of high complexity (Tononi *et al.*, 1994). Segregation refers to the existence of specialized neurons and brain areas, organized into distinct

neuronal populations and grouped together to form segregated cortical areas. Dynamically evolving groups of assemblies of distinct multiple neuronal populations are more likely to be associated with dynamic connectivity. As such, dynamic connectivity and dynamic continuity co-exist as segregation and integration, with the former, implying a differentiation of cognitive states, and the latter, giving rise to the coordinated activation of distributed neuronal populations which enable the emergence of coherent cognitive states. For instance, activity in one neural circuit triggers activity in an overlapping neural circuit so that their integration yields dynamic continuity. Indeed, there is no one fixed spatiotemporal pattern of neural activity associated with a particular cognitive state, but trajectories through neuronal state-space that are continuous in time and space (Spivey, 2007).

Cognitive processes involving continuously changing patterns of neural activity are dynamic processes (van Gelder, 1998). Integration of these dynamical processes across scale is needed to bring about dynamic continuity. Dynamic continuity resulting from the continuous evolution of dynamical systems in a process of “differing and deferring” — a course of action where synaptic connectivity and synaptic transfer is refined by sensory input and learning whereby dynamical connectivity is altered (Globus, 1992). *A priori* for integration is the notion of continuity of dynamical systems across all hierarchical levels of dynamic connectivity. The dynamic continuity through the action of changing the flow pattern across synapses from milliseconds to seconds would suggest that synaptic connectivity disrupts dynamic continuity. However, if cognitive networks of associable representations are regulating patterns of dynamic continuity, then their disruption would signify a termination of that associable representation. Indeed, synaptic plasticity allows for the brain to portray an infinite number of unique trajectories stemming from the structural discontinuities at synapses leading to new associable representations. Consequently, human cognition resides in an infinite dimensional neuronal state-space and the brain considered being dynamically unbounded.

4. Endogenous dendritic coding and memory storage

Investigation of neuronal codes has focused on patterns of axonal spikes (Rieke *et al.*, 1997). Communication by means of action potentials conveys most incoming sensory information and motor commands. However, these differences in spike timing (or spike rates) being axonal transmissions permit highly imprecise informational distinctions regarding cognitive processes that may have taken place in the dendritic arbors. Therefore, these after-effects of dendritic coding might perhaps not come close in providing an approximation of computations that occur endogenously through dendritic coding. Hence, the idea of a temporal code as a means of carrying information is limited because the firing-rate of individual neurons will have an indirect bearing on cognitive function contentiously perceived to be coded in the neural spike train.

Dendritic spikes as dissipative signals enable rich-logic to be encoded during synaptic activity, but cannot simultaneously be used to convey information about aspects of cognitive phenomena during decoding. Instead, endogenous dendritic coding utilizes electrical signals that do not convey differences in neuronal response characteristics across the cellular membrane, but rather use soliton-like ionic waves that drift along endogenous structures in subcellular networks of cortical neurons to decode the imprint of the dendritic code. This has been shown theoretically (Heimburg & Jackson, 2005; Anderson *et al.*, 2009) as well as experimentally (Lin & Cantiello, 1993; Tyszynski *et al.*, 2004). Other hypotheses postulate long-range quantum-mechanical mechanisms for illuminating the associable representations encoded by synaptic activity (Woolf, 1999).

Dissipative dendritic spikes in addition to synaptic potentials interplay with ionic currents within the Debye layer leaving imprints from charge configurations in the form of an ionic “tape”. This can leave a unique pattern permanently stored by the ferroelectric properties of cytoskeletal structures. These imprints form the basis of stored memories that have no semantic representation. Each particular imprint consists of existing ionic charge densities on cytoskeletal structures where counter ionic clouds act as physical representation of shielded ionic charge densities permanently affixed to the surface of the cytoskeletal structure. The imprints from charge configurations are not found on the cellular membranes as they have no ferroelectric properties for permanent charge storage, but on the dendritic cytoskeleton where the dispersion of charge allows ferroelectric capacitors to permanently store charge, and this is read by drifting soliton-like ionic waves directed from different brain regions.

However, recalling memory through scanning of the ionic “tape” requires the spatiotemporal pattern to traverse all the neuronal circuit pathways. In this way, cognitive networks of associable representations form the basis of dynamic continuity with existing pathways erased due to dynamic connectivity and not due to ionic surface charges being overwritten. The inability of new spatiotemporal patterns to successfully find space to establish a new imprint and hence disrupt dynamic continuity is due to extinguished ionic charge — thus vagueness ensued; loss of memory cause pathways that cannot be traversed by the spatiotemporal patterns. The soliton-like ionic wave does not traverse across the synapse, but rather the dynamic continuity that forms cognitive networks of associable representations is aided by the almost continuous cytoskeletal matrix (see Fig. 2).

In order for the regulating patterns of dynamic continuity to follow extant trajectories through neuronal state-space they need to be transmitted across many dendrodendritic synapses to allow the soliton-like wave to scan the ionic tape and retrieve stored memory in the form of shielded ionic charge density configurations. The uniqueness of cognitive networks of associable representations stems from particular types of neural networks during reading of the stored memory that has been traversed by different spatiotemporal patterns. However, if the imprints in the subcellular networks traversed through the same cortical pathways by regulating

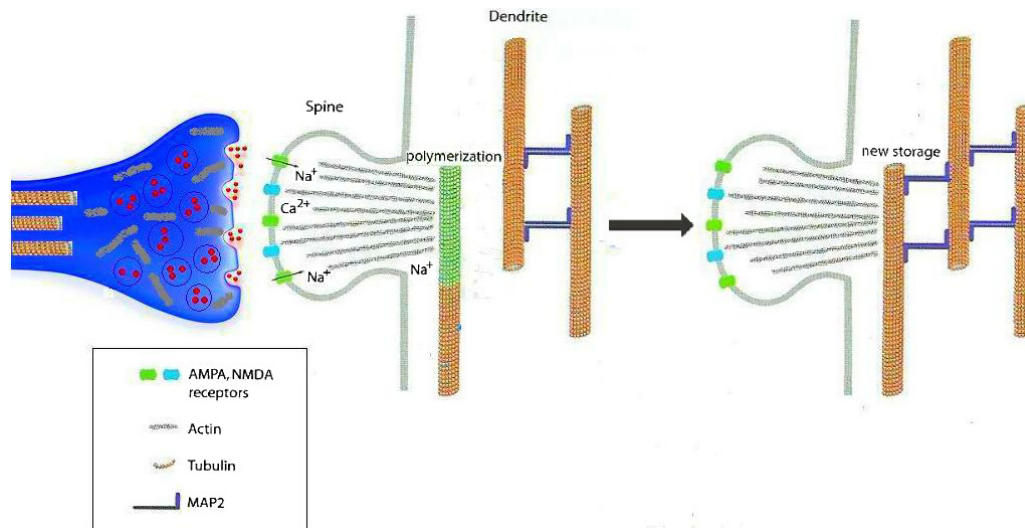


Fig. 2. Schematic diagram illustrating the linkage between the synapse and the intraneuronal cytoskeletal matrix. Presynaptic release of transmitters at a dendrodendritic synapse is activated by changes to the diffusion potential as a result of drifting soliton-like ionic waves along the microtubules and actin filaments. Postsynaptically synaptic input to the spine activates AMPA and NMDA receptors. Actin filaments transmit signals to microtubules in the cortical dendrite that are undergoing polymerization and are in an unstable state. Stabilization occurs through MAP2 bridges between newly polymerized microtubules and adjacent microtubules. A typical cross-section of a dendrite contains 100 microtubules interconnected by MAP2 creating a matrix with input-output to the matrix facilitated by actin filaments. Adapted from Woolf *et al.* (2009).

patterns of dynamic continuity then a semantic representation arising in the neuronal assemblies will manifest into a specific cognitive process.

The scanning is accomplished through the soliton-like wave traversing the ionic “tape” that contains fluctuations of charge densities generating electrical field fluctuations that decode information. One suggestion was that a field theory where fluctuations of ambient potentials in the electrolytic fluid serve as the ionic “tape” (Green & Triffet, 1997). Although Triffet & Green (1984, 1996) were adamant about the extracellular fluid, this has been generalized to occur endogenously (Woolf *et al.*, 2009; Frohlich & McCormick, 2010). Ions of a particular type can be represented by a field, each of which has its own characteristic ionic charge. Clouds of ions or “ionic plasmas” are sources of distributed electric fields. In principle, an unlimited amount of information can be gained from scanning of such an ionic “tape”. The ionic “tape” corresponds to components of the diffusion potential only 10 nV in amplitude (Green & Triffet, 1997) to values close to 1 μ V observable as thermal noise (Poznanski, 2010). These ionic waves drift along endogenous structures to other brain areas across active synapses aided by actin filaments. Moreover, the dendritic spikes are the neural signals responsible for activating dendrodendritic synapses used in imprinting the dendritic code.

The spatial distribution of cytoskeletal structures within cortical neurons subtly explains how stored memory is retrieved and how memory is consolidated. Why is

this unique to cortical neurons? The topological or spatial arrangement of cytoskeletal structures in dendrites of cortical neurons form a dense matrix not found in other cells. In the heart and liver, for example, the cytoskeleton in these cells is not distributed, but elongated around the cell nucleus. So if the spatial distribution of cytoskeletal structures in cortical neurons is a determinant of higher-level cognition then this purports that memory consolidation must be spatially distributed within cortical assemblies. The neocortex has immense number of interconnections between its neurons due to its assembly properties, that is to cooperativity which according to Woolf (1998) means about 50 million cortical networks of associable representations in the lifespan of a human. In the cerebellum, there is almost no feedback mechanism (D'Angelo, 2011) so trajectories as regulating patterns of dynamic continuity that form cognitive networks of associable interactions are based on limited electrical interactions along the cytoskeletal structures. Theoretically, feedback concurrently alters the spatiotemporal patterns to form cognitive networks and as well as recall semantic processes leading towards qualia (see Orpwood, 2010). An example of feedback known to play a role in synaptic plasticity is the backpropagation of action potentials. These backpropagating action potentials drive an influx of Ca^{2+} ions for associative synaptic plasticity in hippocampal and neocortical pyramidal dendrites (Jaffe *et al.*, 1992; Magee & Johnston, 1997; Markram & Tsodyks, 1996) and regulate synaptic efficacy by coincidence with synaptic potentials (Markram *et al.*, 1997). However, the physiological role of synaptic plasticity in memory remains incomplete (Williams & Stuart, 2000) and requires endogenous dendritic coding for a complete understanding of the continuous dynamics underlying cognitive processes. Modeling the role of feedback with models has revealed associative learning (Poznanski, 2002) occurs due to both synaptic activity and backpropagation of action potential trains.

The cytoskeletal structures (e.g., actin-filaments) are polymers that exhibit ferroelectric properties and a nonuniform counter ionic charge density distribution (i.e., polyelectrolyte) at approximately one Bjerrum length or 0.7 nm from the surface where charges that provide a shield to large changes in the ionic strength conditions that occur within the cytoplasm (cf., Priel *et al.*, 2005). It also gives the ferroelectric properties to the polymer for permanent ionic charge storage and has been associated with memory consolidation (Woolf *et al.*, 2009). What causes the storage of the charge to become permanent? In electronics, ferroelectric capacitors retain the polarization permanently because they are in thermodynamic equilibrium. It is well established that lipid bilayer membranes (both cellular and intracellular) act as nonpermanent capacitors (transient decay of charges will leak out/neutralize slowly), while cytoskeletal structures inside the neurons behave as permanent capacitors (permanent charge storage). It should be mentioned that enzymes, too possess ferroelectric properties (Kim *et al.*, 2009), and therefore the theory of biochemical reaction computation underlying molecular interactions cannot be completely ignored as insignificant (McIlroy, 1970; Bhalla, 2002; Ramakrishnan & Bhalla, 2008; Ramakrishnan *et al.*, 2009). In addition to electrical

signals, electrostatic interactions also regulate phosphorylation activity of Calmodulin kinase II enzyme on dendritic microtubules which has been implicated in memory encoding at the level of individual proteins (Hameroff *et al.*, 2010).

Synaptic computations leading to structural modifications between synaptic connections, and which result in changes to synaptic efficiency and therefore, in formations of new spatiotemporal patterns of activity (the hypothesis of synaptic plasticity) believed to be responsible for both learning and memory processes in the brain (Abbott & Regeher, 2004). Theories of synaptic plasticity suggest that during synaptic activation there is a change in the plasticity that determines the strength or weakness of the synaptic connection between cortical neurons. Consequently, to retrieve a specific pathway requires global mechanism of millions of neurons to search for the previously recalled memory. The mechanism of searching to “retrieve” past memories must be identical to that used for decoding the imprints of the dendritic code otherwise neural representations could be assumed to reside in cognitive networks. To retrieve traversed pathways, existing pathways must be first traversed, and the facility of relative easiness of retrieving past memory must be due to the plasticity at synapses allowing for faster retrieval of the neural circuits. However, synaptic plasticity requires synaptic switches that are known to be unfeasible substrates for stable (i.e., permanent) consolidation of memory (Arshavsky, 2006). Notwithstanding the possible biochemical markers for memory, there is mounting evidence for electrodynamical signaling where counter ionic clouds act as physical representations of stored ionic charges along cytoskeletal structures and are sites for stable memory to materialize (Woolf *et al.*, 2009). Therefore, learning is not necessarily new information producing specific physical changes at the synapses, but a continuum of pathways beyond synapses. The entire cell is involved in learning, computation and storing memories. This integrative approach has been neglected by all previous models.

5. Conclusions

In conclusion, we have explained how recalling stored memories involve endogenous dendritic encoding where contextual information remains unaltered for longer periods in neurons as dispersion of ionic charges at macromolecular level. The coding (writing) includes changes in spatial rearrangement of ionic charges in macromolecular formations, determined by dendritic spikes including neurotransmitter release at synapses, while the decoding (reading) can be performed during the drifting of soliton-like ionic waves along cytoskeletal structures traversing the electric field fluctuations induced by fluctuations of the ionic charge densities.

Implications of foregoing views suggest that dynamic anatomy of electrical activity is information-rich. In this article, we amalgamated this perspective with modern cognitive science in order to expound the intricacies involved in cortical networks. Our working hypothesis was that neuroelectrodynamical principles involving subcellular signaling provide a continuum of spatiotemporal patterns

manifested by diffusion potentials which are linked to the dendritic cytoskeleton by endogenous dendritic coding across dendrodendritic synapses leading to trajectories in neuronal state-space as regulating patterns of dynamic continuity that form cognitive networks of associable representations.

Cognitive networks of associable representations are not discrete images of sensation or symbolic representations, but are highly integrated physical modules (i.e., prefrontal cortical areas) where cognitive processes emerging from the executive and attention control of regulating patterns of dynamic continuity are prone to consolidate memory. Based on this idea, we attempted to describe the complex behavior patterns that (1) are non-represented locally but are distributed across brain networks, (2) and how they can be continuous in a hierarchical way. In summary, elucidating the molecular properties of cognitive networks based on physical theory gives us a conceptualization of the spatiotemporal integration in the elucidation of the neural basis of cognition.

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