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# How Activity Regulates Connectivity: A Self-Organizing Complex Neural Network

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***Abstract –*** This work addresses the issue of an appropriate format of *neural representation* from a theoretical viewpoint. If $x_i(t)$ denotes the spiking pattern of neuron $i$, our proposal is that the nervous system uses a *higher-order temporal code* $\langle x_i(t)\, x_j(t - \tau_{ij})\, x_k(t - \tau_{ik}) \ldots\rangle$ instead of average firing rates $\langle x_i(t)\rangle$ to represent mental entities. Temporal binding is the general idea that accurate temporal relationships between neuronal firings may be used by the brain to express perceptual, motor and cognitive relationships. Specifically, our hypothesis is that entities to be bound (local features in primary sensory areas, lexical items in language areas, etc.) are represented by the activation of segments of *synfire chains*, which consist of sequences of synchronous neural groups $P_0 \rightarrow P_1 \rightarrow P_2 \rightarrow \ldots$, feed-forward connections and traveling waves of activity. We postulate that synfire-type activity patterns might constitute the basic components or “building blocks” at the microlevel of the mind’s symbolic abilities, in particular the faculty of *compositionality*—the assembling of elementary features into complex representations. Synfire structures have the required properties to implement the operative objects of perception and language: they are endowed with an internal spatial and temporal structure that allows them to combine in multiple ways and create a virtually infinite hierarchy of composite concepts. The present study focuses on the developmental aspect of this theory and offers a simple explanation for the possible growth of synfire patterns. The connectivity of neocortex displays striking regularities that account for its functional specialization: during pre- and post-natal development, the reorganization of synaptic contacts is guided by ongoing bioelectrical activity and competitive interactions. Based on this observation, we propose a model of cortical self-structuration showing the spontaneous emergence of ordered synfire chains, a phenomenon that can also be described as *spatiotemporal pattern formation*. An initially disordered network characterized by broad diffuse contacts and low stochastic firing undergoes a process of “focusing of innervation”, accompanied by a gradual increase in sustained correlated activity. At each time $t$, the state of the network consists of binary action potentials $\mathbf{x}(t) = \{x_i(t)\}_{i=1 \ldots N}$ and real-valued synaptic weights $\mathbf{w}(t) = \{w_{ij}(t)\}_{i,j=1 \ldots N}$. This state evolves according to three laws: (a) neuronal activation, following a linear-nonlinear Poisson rule; (b) synaptic plasticity, where weight variation depends on the fine temporal correlation between pre- and postsynaptic neuronal signals; (c) intersynaptic competition, imposing that all outgoing and incoming weight sums be conserved at all times. The network also contains a few “seed” neurons sending out stronger connections than average. The outcome of this dynamics is the recursive growth of synfire chains, akin to the growth by accretion of crystal structures from inhomogeneities. Chains extend in length before widening and typically present a mature “trunk” followed by a “beveled tip” of immature groups searching for new neurons to recruit. In conclusion, the theoretical claim carried by our model is that compositionality can arise from the gradual ontogenetic development of the nervous system during the early stages of synaptogenesis. In this, we join Chomsky’s conception that the innate predisposition for the *faculty* of language (as opposed to any specific language) might involve a growth and maturation of the nervous system comparable to a limb or an organ. We suggest that neocortex is another “self-made tapestry”, similarly to the vast majority of natural complex systems—physical, chemical, biological or social. Moreover, its motifs can dynamically bind and create new combinations, thereby providing the basis for learning. Our self-structuration model offers an intermediate or *mesoscopic* level of description of cognitive abilities, at a finer granularity than the macroscopic symbols of AI but higher structural complexity than the microscopic neuronal activities of connectionism.