Physics of Life Reviews

Computational modeling aids in linking structure, dynamics, and function of neural systems

--Manuscript Draft--

Manuscript Number:	
Article Type:	Comment
Keywords:	Theoretical neuroscience; cortical structure; dynamics; function; spatial/temporal scales; mesoscopic neurodynamics; neural oscillations; developing brain; neural networks; neurocomputational models
Corresponding Author:	Hans Liljenström, Ph.D. Swedish University of Agricultural Sciences: Sveriges lantbruksuniversitet Uppsala, SWEDEN
First Author:	Hans Liljenström, Ph.D.
Order of Authors:	Hans Liljenström, Ph.D.

Computational modeling aids in linking structure, dynamics, and function of neural systems

A Commentary on Wright, J. J., & Bourke, P. D. "The growth of cognition: free energy minimization and the embryogenesis of cortical computation". Physics of Life Reviews.

Hans Liljenström

Agora for Biosystems
SE-193 22 Sigtuna, Sweden
and
Biometry and Systems Analysis Group
Swedish University of Agricultural Sciences
SE-750 07 Uppsala, Sweden

Email: hans.liljenstrom@slu.se

One of the major tasks for theoretical neuroscience is to propose and investigate relations between structure, dynamics and functions, as well as between different spatial and temporal scales of neural systems. Wright and Bourke (W&B) wrestle forcefully with both of these tasks, suggesting how the developing brain through neural oscillations might enable the emergence of cognitive functions. In addition to bridging different levels of neural organization, the authors also connect two interesting theories, the Free Energy Principle and the Dynamic Logic theory. This endeavor relates nicely to Walter Freeman's mesoscopic neurodynamics (Freeman, 2000; Liljenström, 2018), as well as to John Hopfield's seminal work on recurrent neural networks for associative memory (Hopfield, 1982, 1984), without explicitly referring to it. I will in the following discuss some of these links.

For biological systems, it is essential to be stable to short term fluctuations, or common insignificant events, while it should also be able to react to weak signals and rare important events, as well as adapting to long-term changes. This stability–flexibility dilemma is of particular concern for neural systems, which presumably have evolved to provide an efficient interaction with the environment. Flexibility, or adaptability, can be considered at several time scales. At an evolutionary scale, there is a slow adaptation, which is genetically determined, resulting in the gross structure of the nervous system and the initial neural organization of the developing brain. However, already in the fetus, the neural organization of the brain is modified by various epigenetic processes, with molecular, cellular, and network dynamics acting at much shorter time scales.

W&B describe convincingly how mesoscopic neurodynamics (c.f. Freeman, 2000), in particular synchronous firing and network oscillations can shape cortical structure, enabling an efficient information processing important for learning and other cognitive functions. Their focus is on the growth of columnar structures during embryogenesis, facilitated by the synchronous firing of neurons, but modifying processes, such as network pruning, input from the developing sensory organs, various hormones etc are also important to consider. Such influences give the brain a "final" unique structure that is not possible to predict from the genes alone. Learning that occurs throughout life modifies the neural structures continuously, and provides adaptation at an intermediate time scale. At even shorter time scales, the neurodynamics of the brain, partly regulated by neuromodulators (e.g. acetylcholine and serotonin), provide rapid adaptation to fast changes in the external and internal environment (Liljenström & Hasselmo, 1995).

When approaching the challenging problem of interactions between different spatial and temporal scales, computational models can prove useful, and sometimes the sole method of investigation. The main problem for the modeler, however, is to find an appropriate level of system structure, as well as an objective function that can describe system dynamics. W&B wisely focus on a mesoscopic description, with minimization of free energy as the objective function. Similarly, Hopfield showed how the minimization of an energy function calculated for recurrent artificial neural networks with symmetric connection weights could enable storage and recall of memory states (Hopfield, 1982, 1984). However, these memory states are point attractors, without any oscillatory dynamics, which instead could result from more realistic network structures, using asymmetric connections and feedback loops of excitatory and inhibitory network nodes (representing populations of neurons).

We have used this type of modified Hopfield nets to study associative memory in the olfactory cortex (Liljenström, 1991, 1995; Wu & Liljenström, 1994), where learning and recall instead are provided by limit cycle memory states and strange attractor dynamics. Computer simulations demonstrate how the nonlinear dynamics, including oscillations and even chaos-like behavior, can give flexibility to the system and increase the efficiency of information processing in associative memory tasks.

W&B emphasize the role of neuronal synchrony for the development of cortical columns and cognitive functions. (It would be interesting to know if the W&B model could also account for the development of the olfactory cortex, which is neither columnar, nor topologically preserving). Our computer simulations of electrical gap junctions demonstrate the experimental observations (Peinado et al., 1993; Jefferys, 1995) that such non-synaptic effects may also enhance synchrony, increasing and stabilizing cortical oscillations, while suppressing high-frequency components (Aronsson & Liljenström, 2001), which may have consequences for cortical structure and function.

In particular, we have used our computational models to investigate how modification of network structure, for example due to pruning and sprouting, could affect neural and mental order and disorder (Liljenström, 2003). This is following a hypothesis by Saugstad and others (Feinberg, 1982; Saugstad, 1989, 1994; Siekmeier and Hoffman, 2002) that mental disorders could be connected to the pruning of the neural networks of the developing brain. During initial development, many structural elements such as neurons, dendrites, axons, and synapses are overproduced, enabling the system to fine-tune itself subsequently to account for environmental factors, where competitive processes often govern the refinement of the structure. This structural refinement is a necessary part of neural self-organization and provides further adaptability. The pruning, which decreases the total number of synapses, is believed to result in an optimally efficient neural network, as the developing brain integrates and consolidates early experiences. In the last major step in brain development, some 40% of the neuronal synapses are eliminated. Both too early and too late shut down of the pruning process could lead to mental disorders. In early maturers, manic depressive psychosis is more common, while late maturers more often develop schizophrenia (Saugstad, 1994).

Our simulations show that a high interconnectivity, with extensive long-range excitatory connections, and more local inhibitory connections, can be extremely robust to network pruning and external or internal fluctuations. An oscillatory dynamics, resulting from a proper balance between excitation and inhibition, is another factor that provides both flexibility and stability to the system. In addition, such a dynamics is more energetically advantageous than a non-oscillatory dynamics. A pruned network is also more efficient in terms of energy usage (less synapses involved) and network activity levels, and it gives a more accurate learning/recall (Liljenström, 2003, 2010).

Although some earlier attempts have been made in linking structure to dynamics and function of neural systems, W&B have taken a great leap forward with their experimentally motivated model. Their approach is exactly of the type that is so much needed in order to get a deeper understanding of the complex relations between various spatial and temporal scales of neural systems. W&B have successfully demonstrated how computational modeling can complement experiments in moving neuroscience forward, in particular with respect to the major challenge of relating neural structures to cognition and consciousness.

Acknowledgement
This publication was made possible through the support of a joint grant from the John Templeton Foundation and the Fetzer Institute. The opinions expressed in this publication are those of the author and do not necessarily reflect the views of the John Templeton Foundation or the Fetzer Institute.

References

Aronsson P. and Liljenström H. (2001) Increased dynamical order with non-synaptic cortical interaction. *BioSystems* **63**:43-56.

Feinberg I. (1982) Schizophrenia: caused by a fault in programmed synaptic elimination during adolescence? *J Psychiatr Res* **17**:319–334.

Freeman W.J. (2000) *Neurodynamics*. Springer.

Jefferys, J. G. R.(1995) Nonsynaptic modulation of neuronal activity in the brain: Electric currents and extracellular ions, *Physiological Reviews,* **75**:689-723, 1995.

Liljenström H. (1991) Modeling the dynamics of olfactory cortex using simplified network units and realistic architecture. *Intl. J. Neural Systems* **2**:1-15.

Liljenström H. (1995) Autonomous learning with complex dynamics. *Intl. J. Intelligent Systems* **10**:119–153.

Liljenström H. & Hasselmo M.E. (1995) Cholinergic modulation of cortical oscillatory dynamics. *Journal of Neurophysiology* **74**:288–297.

Liljenström, H. (2003) Neural stability and flexibility - A computational approach. *Neuropsychopharmacology* **28**: S64-S73

Liljenström H. (2010) Network effects of synaptic modifications. *Pharmacopsychiatry* **43**: S67 – S81

Liljenström H. (2018) (ed.) Freeman Neurodynamics. Special issue of *J. Consc. Studies*, Vol. 25, Nos 1-2. Imprint Academic.

Peinado A. Yuste, R., and Katz, L.C. (1993) Gap junctional communication and the development of local circuits in neocortex. *Cereb. Cortex* **3**:488-498.

Saugstad L.F. (1989) Age at puberty and mental illness. *Br J Pshychiatry* **155**: 536–544.

Saugstad L.F. (1994) The maturational theory of brain development and cerebral excitability in the multifactorially inherited manic depressive psychosis and schizophrenia. *Int J Psychophysiol* **18**:189–203.

Siekmeier P.J. and Hoffman R.E. (2002) Enhanced semantic priming in schizophrenia: a computer model based on excessive pruning of local connections in association cortex. *Br J Psychiatry* **180**:345–350.

Wu X. and Liljenström H. (1994) Regulating the nonlinear dynamics of olfactory cortex. *Network: Computation in Neural Systems* **5**:47–60.

Declaration of Interest Statement

The author declares that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Hans Liljenström, PhD, Prof.