Minds, Modules and Memory: Exploring Networks of the Nervous System from the Worm to the Primate*

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Abstract—Nonlinear dynamics of neuron-neuron interaction via complex networks forms the basis of all brain activity. How such inter-cellular communication gives rise to behavior of the organism has been a long-standing question. Here we first explore the evidence for the occurrence of such mesoscopic structures in the nervous system of the nematode *Caenorhabditis elegans* and in the macaque cortex. Next, we look at their possible functional role in the brain. We also consider the attractor network models of nervous system activity and investigate how modular structures affect the dynamics of convergence to attractors. We conclude with a discussion of the general implications of our results for basin size of dynamical attractors in modular networks whose nodes have threshold-activated dynamics. As such networks also appear in the context of intra-cellular signaling, our results may provide a glimpse of a universal (i.e., scale-invariant) theory for information processing dynamics in biology.

The discoveries over the past decade of universal principles underlying complex networks occurring in biological, social and technological contexts has instigated a massive effort among physicists to explain such features using techniques from statistical physics and nonlinear dynamics [1]. Initially, the focus had been on exploring and explaining the macroscopic global features of such networks characterized by, e.g., the small-world network properties (coexistence of local clustering with short average path length) or scale-free degree distribution. However, recently more attention has been devoted to understanding the genesis of *mesoscopic* features of networks. These include the existence of *motifs* (statistically significant over-representation of certain subnetworks) at the small scale, and, *modular* and *hierarchical* structures in the large scale. Modularity is characterized by the existence of communities, identified by the relatively larger density of connections within them compared to that between different communities. These structurally defined partitions can also have modular functionality, so that elements belonging to different communities may be specialized for performing distinct functions. Mesoscopic analysis of networks, e.g., that of the somatic nervous system of the nematode *Caenorhabditis elegans* [2], can reveal the critical importance of certain nodes which act as coordinating agencies between different modules. The ubiquity of mesoscopic structures has raised the inevitable question: what is the possible utility of modularity or hierarchy? In earlier work, we have shown that communities evolve spontaneously when a network is performing multi-constrain optimization, viz., minimizing (i) average path length, (ii) total number of links and (iii) instability with respect to small perturbations [3].

However, possibly of more relevance for understanding the modular networks that occur in the brain is an important dynamical consequence of the community structure: the existence of two very different time-scales, one corresponding to fast intra-modular and the other to slower inter-modular or global processes [4]. This property can be generalized to networks having a hierarchical organization with modules at multiple levels [5], which can exhibit a large number (>>2) of distinct time-scales [6]. It is apparent that separation of the time-scales for the dynamics at the local and global levels is extremely important in the context of synchronization of activity of clusters of neurons, which is necessary in short range for communication and coordination but if occurring at a longer scale can result in undesirable consequences such as epilepsy. However, there are other advantages to modularity for information processing in the brain. For instance, we have shown that convergence to desirable attractors of brain dynamics is more efficient for networks having modular organization [7]. This result is of potential relevance in explaining the appearance of communities in the cortico-cortical networks of mammals, in particular, in the cat cortex and macaque cortex. It suggests a possible universal principle governing the structure-dynamics relation in biological networks involved in information transfer and processing, not only in the brain but also within the cell.

REFERENCES


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