Neuronal ensembles as elementary representations in the nervous system

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Studies of the nervous system are performed at multiple system levels, beginning with the structure and function of single molecules (e.g. ion channels), electrochemical processes at the level of single cells (e.g. generation of action potentials, synaptic transmission), activity in multi-neuronal networks (e.g., processing of visual inputs in the retina), large-scale spatiotemporal patterns in the nervous system (e.g., brain-wide activation patterns during cognitive task performance) and, ultimately, at the cognitive-behavioral level of the whole organism (perception, motion, decision making, emotions etc.). In real live, processes at all these levels work together, such that simple bottom-up or top-down models of brain function are far too simple.

This complexity is one of the reasons why mathematical approaches are indispensable in modern neuroscience. We are dealing with highly parallel data, e.g. simultaneous recordings from multiple neurons in electrophysiology, or from millions of volume elements in functional brain imaging. In addition, the emergent properties of complex systems like neuronal networks cannot be simply predicted from linear causal relations and, thus, are often inferred from computer simulations. Third, we are beginning to reveal more and more structural details of the brain – the functional consequences of these boundary conditions are again a topic for mathematicians and network scientists.

In my presentation, I will exemplify some major research problems and approaches of modern neuroscience, focusing on the level of neuronal networks. Our leading question is: How does the brain represent a perception, a memory, a planned action or a motor program? Most neuroscientists agree that this 'coding' is performed by multiple cells which are co-activated in a reproducible manner. These sets of neurons are called ensembles or, in other research traditions, assemblies. They can be reproducibly activated even by incomplete input patterns, forming stable spatio-temporal structures or (in one specific approach) attractors in the network's state-space. In most cases, activation of ensembles happens on top of synchronous network oscillations which provide a temporal scaffold (or 'clock') for coordination of the multi-neuronal activity pattern.

In this presentation, we shall discuss the concept of ensembles and its implications for the multiplicity, stability and plasticity of different representations. We will highlight some specific questions based on own and other's data, mainly from memory-forming networks in the rodent hippocampus. Key questions are: What are the key properties of hippocampal ensembles? How are single neurons bound into reproducible spatiotemporal patterns? How are non-participating neurons reliably suppressed during activation of a given ensemble? How are local ensembles bound into large-scale functional networks?

All of these questions require multidisciplinary approaches including cell and systems physiology, behavioral neurosciences and, importantly, advanced data analysis and mathematical modelling. The importance of (and sometimes lack of) generally accepted quantitative models of neuronal networks, their cellular constituents and their large-scale effects will become clear from each of the multiple open questions mentioned during the presentation.