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A MODULAR NEURODYNAMICS APPROACH TO BRAIN FUNCTION

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Abstract: The hypothesis that cognitive abilities of biological brains are based on complex dynamical properties of modular neural networks is not only well-founded by experimental results from the neurosciences, but it is also suggested by the observation that already small artificial neural networks with recurrent connectivity inherit complex dynamical features. Examples are given and dynamical effects of coupling such systems, like synchronization of subsystems, are discussed. Presented results can be of relevance for a new interpretation of biological findings.

Oral presentation preferred.

Summary (Oral presentation preferred)

The widespread recurrent connectivity structures found in biological brains, together with the existence of excitatory and inhibitory synapses, imply the possibility of complex neural dynamics and, in fact, brain imaging techniques as well as electrode data show oscillatory action of neurons and structured space-time patterns of neural activity over large brain areas. Furthermore, anatomical as well as physiological observations indicate that neurons are grouped together into functional circuits. These small neural populations, like the hypothesised hypercolumns, are assumed to represent basic building blocks of a modular brain organisation. Although such modules can be composed of as many as 10^5 neurons, already 2-neuron circuits like the recurrent inhibitory loop (Wilson-Cowan) or 3-neuron circuits, serving, for instance, as central pattern generators, are considered to represent the basic feedback mechanisms regulating neural activity.

All these findings suggest that complex neural dynamics is the very basis for higher brain functions and cognitive abilities. Although dynamical approaches to cognition date back to the cybernetics era, even with the detailed knowledge acquired today it is difficult to explain, how function arises and changes, how it is associated to structure, and to decide, if it is related to local or collective phenomena. Based on ideas coming from dynamical system theory and complex systems research, as well as on behaviour oriented approaches to embodied cognition, we will use simulation results for small artificial neural networks and their couplings as a guiding metaphor for the dynamical interpretation of biological brain function.

The simulated neuromodules are composed of standard additive neurons with strictly positive sigmoidal transfer function and have recurrent connectivity structures with excitatory and inhibitory synapses. They inherit already complex dynamical features like, for example, variable oscillatory modes including chaos, and the existence of many different accessible oscillatory modes at the same time.

Variability of behaviour modes is due to the fact, that these networks – as their biological counterparts, are to be described as parameterised dynamical systems, where reasonable parameters are "slowly" varying variables like synaptic strengths, bias terms, "stationary" inputs, and the like. Here, "slow" refers to the activity dynamics describing changes in membrane potential of neurons, which is considered to be "fast". Parameter changes may be induced by driving external signals, by activity related learning procedures, by biochemical influences, etc. Critical parameters, for which the behaviour of the network changes qualitatively, are called bifurcation points. We argue, that a well-contrived balance of excitation and inhibition in a network keeps parameters in the neighbourhood of bifurcation points, so that different functional modes can be easily accessed in a short time.

Furthermore we want to emphasise the fact, that for fixed parameter values neuromodules can have different non-trivial attractors (defining behaviour modes) at the same time; for instance, a p-periodic attractor may co-exist with a chaotic attractor. Thus it depends on the initial conditions which system behaviour is finally observed. Co-existence of different attractors may lead to the observation of "generalised hysteresis" phenomena: Changing parameter values slowly while crossing a corresponding bifurcation set, which of the attractors is asymptotically reached by the system depends on the direction from which one has entered this so called hysteresis domain. Crossing the whole of this hysteresis domain with varying parameter values will lead to sudden jumps in the qualitative behaviour of the system. In the simplest case this refers to bi-stability of a system. As we will show, already 2-neuron networks have periodic attractors co-existing with quasi-periodic or chaotic ones, and in 3-neuron networks also coexisting different chaotic attractors can be observed.

In our studies we lay emphasis on chaotic dynamics, not because we believe that chaotic dynamics will play an essential role for functional neural processing, but because of the following fact: If a neural circuit allows for parameter values such that chaotic behaviour is observed, then in general, for the same architecture, there also exist parameter values for any kind of periodic behaviour (including, of course, fixed point attractors). In this sense, these so called "chaotic" neuromodules provide a large reservoir of dynamical properties. From this reservoir, a learning algorithm or convenient external driving signals may select those parameter values which lead, perhaps in co-operative interaction with other neuromodules of the system, to a desired or appropriate functional behaviour.

We want to point out, that with respect to the neurodynamics approach to cognitive systems, we understand attractors only as classifying instruments. For neural networks serving as embodied cognitive systems - and this is the essential aspect of biological brains here – the dynamics always will be that of a driven system. Of relevance for the behaviour of such a systems is only the basin structure of phase space defined by the attractors. And it is the transients in one and the same basin of attraction which are related to a specific functional brain process. Of course, the number, structure and size of basins, as well as their defining attractors, are controlled by the parameters of the modules, and thus, different modes of behaviour may appear or disappear while crossing corresponding bifurcation sets.

If one thinks about these small neural networks as basic building blocks for larger systems, i.e. using them as interacting modules, the description of dynamical features becomes even more difficult, because the (recurrent) coupling of non-linear subsystems can lead to many undesired or unexpected behaviours of the composed system. Describing the appearance of cognitive processes as emergent phenomena in large modular neural systems we enter complex systems research. As a first step we present synchronization effects in subsystems, to which we ascribe the effective reduction of phase space, accessible for other neural groups, as its main functional meaning. In addition we present examples of functionally coupled neuromodules which were derived as evolved networks, generating interesting behaviours for autonomous robots.