Multi-Input, Multi-Output Nonlinear Dynamic Modeling to Identify Biologically-Based Transformations as the "Cognitive Processes" Represented by the Ensemble Coding of Neuron Populations

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Abstract

The successful development of neural prostheses requires an understanding of the neurobiological bases of cognitive processes, i.e., how the collective activity of populations of neurons results in a higher-level process not predictable based on knowledge of the individual neurons and/or synapses alone. We have been studying and applying novel methods for representing nonlinear transformations of multiple spike train inputs (multiple time series of pulse train inputs) produced by synaptic and field interactions among multiple subclasses of neurons arrayed in multiple layers of incompletely connected units. We have been applying our methods to study of the hippocampus, a cortical brain structure that has been demonstrated, in humans and in animals, to perform the cognitive function of encoding new long-term (declarative) memories. Without their hippocampi, animals and humans retain a short-term memory (memory lasting approximately 1 min), and long-term memory for information learned prior to loss of hippocampal function. Results of more than 20 years of studies have demonstrated that both individual hippocampal neurons, and populations of hippocampal cells, e.g., the neurons comprising one of the 3 principal subsystems of the hippocampus, induce strong, higher order, nonlinear transformations of hippocampal inputs into hippocampal outputs. For one synaptic input or for a population of synchronously active synaptic inputs, such a transformation would be represented by a sequence of action potential inputs being changed into a different sequence of action potential outputs. For multiple, asynchronous synaptic inputs, such a transformation would be represented by a spatio-temporal pattern of action potential inputs being changed into a different spatio-temporal pattern of action potential outputs. Our primary thesis is that the encoding of short-term memories into new, long-term memories represents the collective set of nonlinearities induced by the 3 or 4 principal subsystems of the hippocampus, i.e., entorhinal cortex-to-dentate gyrus, dentate gyrus-to-CA3 pyramidal cell layer, CA3-to-CA1 pyramidal cell layer, and CA1-to-subicular cortex. This hypothesis will be supported by studies using the in vitro hippocampal slices, and in vivo hippocampal multi-neuron recordings from animals performing memory tasks that require hippocampal function. The implications for this hypothesis will be discussed in the context of "cognitive prostheses" – neural prostheses for central, cortical brain regions believed to support cognitive functions, and that often are subject to damage due to stroke, epilepsy, dementia, and closed head trauma.