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Origin of Complex Spike Synchronization in Neuronal Circuits

Yuji Ikegaya

Grad School of Pharmaceutical Sciences, The University of Tokyo

Synchronized spikes prevail in cortical networks. Their modulations are commonly found in relation to attention, sensory processing, and motor behaviors and are implied in perceptual binding. From computational aspects, spike synchronization is crucial in information propagation. As single synapses are weak and stochastic, spikes are unable to propagate stably to downstream networks unless they are synchronized among neurons. Moreover, synchronized spikes efficiently induce long-lasting synaptic plasticity, depending on their relative timings between presynaptic and postsynaptic neurons.

Spikes can synchronize not only between a pair of neurons but also among a set of neurons, often yielding complex population dynamics, as in cell assemblies, synfire chains, and neuronal avalanches These events usually emerge through autoassociative recurrent networks, but they do not necessarily require direct synaptic connections among all participating neurons. Rather, they may develop through sparse interactions among relatively small groups of neurons. Indeed, local correlations between neighboring cells can at least partly report globally synchronous activity at the population level. Independent studies have already addressed the topology underlying "functional" connectivity among multiple active neurons or "synaptic" connectivity at single neuron resolution, but no studies have made direct comparisons between spatiotemporal spike patterns and the relevant synaptic wiring architectures in large neuronal networks. Therefore, little is known about the functional and anatomical relationships during network operations. These facts have motivated us to elucidate the linkage between local spike correlations and their collective dynamics.

To elucidate how synchronization emerges from active neuronal networks, we exploited high-speed functional multineuron imaging, dynamic clamp recording, and optical mapping of synaptic connections in hippocampal CA3 networks ex vivo. Spontaneous activity was coordinated by numerous synchronized spikes, which were timed with millisecond precision. Synchronous events were power-law distributed in size, and individual events engaged different combinations of assemblies of highly synchronized neurons. Neurons constituting the assemblies were more apt to be synaptically connected, shared more common presynaptic excitatory neurons, and thus received more correlated excitatory synaptic inputs. Moreover, outputs from a CA3 neuron assembly were preferentially converged onto identical CA1 neurons. Thus, network synchronization recruits complex neuronal ensembles that develop through small-world-like network architectures, which may serve as modular channels of information flow.