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Highly nonrandom synaptic connectivity and spontaneous ongoing fluctuation in cortical networks

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Abstract– Synaptic connectivity of local cortical circuit is highly nonrandom. Connection strength among neurons in the cortex is not distributed on normally or on the Gaussian distribution. Rather, it is well described with a long-tailed, typically the lognormal distribution. The skewed distribution indispensably contributes to robust generation of spontaneous ongoing fluctuation in cortical circuit, which is now thought as a key feature to realize flexible and high performance stochastic computation in the brain. In this study, introducing recent results of studies about synaptic connections in cortical circuit, we provide a mathematical background of fluctuation generation owing to the lognormal distribution.

1. Introduction

Synaptic connections among neurons in local cortical circuit are neither homogeneous nor random [1]. Strength of connections, or amplitude of excitatory postsynaptic potential (EPSP) is distributed with a long-tailed distribution, typically the lognormal distribution [1-3]. The lognormal distribution of connection strength means that while almost all connections are weak, a few connections are extremely strong. Actually, while typical amplitude of EPSPs are less than 1 mV, amplitude of a few connections reach to about 10 mV that is dozens times larger than the typical value of amplitude.

Sparse strong connections are not randomly distributed in the cortical circuit. Physiological experiments reported that strong connections form “cluster” with significantly higher probability from naively expected from average connection rate of the network [1]. For pairs of neurons, if one of neurons receives synaptic input from another with large amplitude, probability of existence of connection with opposite direction is significantly high. Also, correlation between connection strengths of forward and backward connections for pair of neuron is high if exists. Similarly, for triplet neuron, the cluster coefficient of them, i.e. probability that two of them are connected when these two are connected to the other one, is significantly high for strong connections. It is also reported that the cluster structure closely related receptive field of neurons in primary sensory cortex [4].

Interestingly, the nonrandom features of synaptic connectivity affect crucially on spike dynamics of population of neurons in the network. Especially, recent theoretical studies revealed that highly heterogeneous distribution of EPSP and cluster structure of sparse strong connections are key to robustly generate spontaneous and ongoing fluctuation of cortical networks [5-8], which is actually observed in vivo and in vitro experiment and known as a ground state of cortex [9, 10]. Robustly generated fluctuation in cortex is now thought as an indispensible factor of cortical computation. Accompanied with nonlinearity of neurons and population dynamics of neurons, the intrinsic fluctuation adjusts neural response and allows the network to have rich variety of states and responses.

In this study, we introduce recent developments of synaptic connectivity in local cortical circuit including cluster structure of them. Then develop a mathematical framework to characterize synaptic communication with the lognormal strength distribution. Owing to the long-tail nature, synaptic interactions on the network give very differently outcomes from normally connected network with for instance with the Gaussian distribution. We discuss how the specific feature of the lognormal distribution relates intrinsic fluctuation and computation in the brain.

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