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Basic study on network topology and learning for abnormal firing in a neural network model of spontaneous brain activity

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The brain is composed of a network of many neurons. Important functions such as memory, attention, movement control etc. are realized here. Because of the complexity of the electrophysiology of the neurons and the dynamics of a network of many neurons, the mechanism of such brain functions is far from being understood in detail. Towards a comprehensive understanding of the brain function, the neuroscience investigates the brain with an interdisciplinary approach combining biology, physiology, medicine, mathematics, physics, and engineering.

In the cerebral cortex, a network of neurons is known to maintain an irregular low-rate firing activity even when there is no external stimulus. This phenomenon is known as " spontaneous cortical activity. " The spontaneous activity is characterized by (1) low firing rate of about few Hz, (2) asynchronous firing between the neurons, and (3) non-periodic irregular firing. Until recently, such firing activity was considered to play no vital role in the neural information processing. However, new studies suggest potential functions of the spontaneous activity such as responsiveness of the neuron to external stimuli and efficient information transmission in the brain. This motivates mathematical modeling of the neural network to elucidate the spontaneous activity in the brain. The conventional models can be divided into two types. In the first type, the irregular network activity is represented as ‘‘ noise ’’ added to individual neurons or synaptic connections. This type, however, puts the originating source of the noise into black-box and provides no deep insight into the spontaneous activity. The second type, on the other hand, takes into account more detailed neuronal physiology and modeled the irregular firing activity as emerging from the intrinsic network dynamics. Despite many models proposed so far, the second type was not so successful about reproducing the low firing activity observed in the real experiment. A remarkable model was recently proposed by Teramae et al., who focused on the log-normal distribution of the excitatory postsynaptic potential (EPSP). They have shown that the log-normal distribution of the EPSP was the key to maintain the low and irregular firing activity in the neural network. Their model provided the most reasonable understanding of the spontaneous activity using the plausible condition of the physiological experiment.

Although the model of the log-normal distribution presented a breakthrough in this field, their study is still preliminary in the sense that only the first order distribution was considered for the EPSP. More comprehensive study should take into account the influence of the second- and higher-order distribution of the EPSP and the network topology on the spontaneous activity.

For instance, if two neurons are bidirectionally and strongly connected with each other, a long-lasting spiking activity can be maintained within a chain of these neurons. Such a chain may serve as an oscillatory source, from which the spike signals can spread to the neighboring neurons. In this way, the oscillatory pair may cause an abnormal firing activity in the brain.

As a possible brain function to suppress such an abnormal firing, we consider “learning ’’ in the neural network, since the synaptic plasticity is expected to avoid the strong correlation between the interconnected neurons.

The purpose of this research is to clarify the influence of the network topology on the spontaneous firing activity and study the possible function of the learning to avoid the abnormal firing activity of the neurons. First, simulation study of the neural network clarifies the influence of the network topology on the neuronal firing activity. Two quantities are utilized to characterize the network topology: (1) correlation of the EPSPs between a pair of bidirectionally coupled neurons and (2) ratio between bidirectional coupling and unidirectional coupling.

First, a simulation using the quantities close to the physiological values reported in the experimental study was compared with the one using the quantities far from the physiological values.

As the result of using the physiological values, almost all excitatory neurons fired with a low firing rate in an irregular manner. This reproduced the basic features of the spontaneous activity. On the other hand, as the result of using the non-physiological values, only some group of excitatory neurons fired in a very high firing rate. Here, other neurons were silent without much firing. Such firing activities of the neurons are considered to be abnormal and produce a large gap between the average firing rate of all neurons and the average firing rate of a small number of highly activated neurons. We use this gap as a quantity to characterized the abnormal activity.

Next, we studied the influence of the network topologies (1) and (2) on the network dynamics in more detail. Our simulations showed that increase in the correlation of the EPSPs between a pair of bidirectionally coupled neurons leads to abnormal firing activity, whereas increase in the ratio between bidirectional coupling and unidirectional coupling accelerate the transition to abnormal activity. This implies that the two quantities provide important characteristics to anticipate the abnormal firing activity.

As a brain function to avoid the network topology, a learning scheme based on the spike-timing dependent synaptic plasticity (STDP) was further introduced. In the simulation, the learning was applied to a network of neurons, which produced an abnormal firing activity due to the network topology far from the physiological value. The results showed that the high correlation of the EPSPs was gradually decreased as the learning proceeded. This implies that the learning has a vital role of leading the network topology to a normal topology to maintain the spontaneous firing activity.

To conclude, this research clarified the influence of the network topology on the firing activity of the cortical neural network and showed that physiologically plausible setting of the topology realized a spontaneous activity, whereas implausible setting leaded to abnormal activity. Simulation of the learning showed that the learning corrects the network topology to normal values to maintain a spontaneous firing activity. This implies an important role of the learning that can potentially avoid the abnormal firing activity such as epilepsy in a healthy brain.