Possible Role of Synchronous Input Spike Trains in Controlling Function of Neural Networks

Toshio Aoyagi, Takaaki Aoki

Kyoto University, Kyoto, Japan
aoyagi@acs.i.kyoto-u.ac.jp,
takaaki@acs.i.kyoto-u.ac.jp,

CREST, JST (Japan Science and Technology)

Abstract

To investigate how temporal structure of neuronal activities affects the function of neural networks, we consider the effects of synchronous firing inputs on two typical functions of neural networks; winner-take-all competition and associative memory. Using the network of integrate-and-fire neurons, we study their effect on these functions. The results show that uncorrelated discharge among neuronal inputs can realize the standard winner-take-all competition, whereas synchronization of the neuronal inputs prevents such competition. Furthermore, in the case of associative memory model, we present that the timing of the next retrieval can be controlled by such synchrony-asynchrony transition of external inputs.

(1000 WORD SUMMARY)

Synchronous activity among ensembles of neurons is a ubiquitous phenomenon observed in many regions of the brain. In particular, recent experiments suggest that stimulus-dependent synchrony provides an efficient mechanism to bind features detected by sensory cortices into a single perceived object. Another experiments show that the degree of synchrony is frequently modulated by switching attention. From these results, it is suggested that synchronous neuronal activity may play an important role in realizing the brain functions efficiently. Moreover, to make use of the temporal structure of neuronal spike trains is thought to be one of potentially powerful information processing strategy in the neuronal systems. Currently, many theoretical works have been reported so far. In most cases, they have focused mainly on what dynamical mechanisms of neuronal systems can yield the synchronous firing in the network. Consequently, the knowledge and the analytical techniques concerning the synchronization in the neuronal systems have greatly progressed. On the other hand, how such synchronous neuronal activities affect the function of the neural networks has been studied in fewer cases, and the role of synchrony in the function of neural networks still remains unclear.

However, a recent modeling study reveals that winner-take-all mechanism in neural circuits is remarkably sensitive to the timing of neuronal spike inputs (E.D.Lumer 2000). Therefore, uncorrelated discharge among neuronal inputs can realize the usual winner-take-all competition, whereas synchronization of the neuronal inputs tends to prevent such competition. This is very interesting property because the temporal structure of cortical activity may play a crucial role in selecting information for the control of attention and voluntary motor action. From the point of theoretical view, however, the question arises: what conditions are required to control winner-take-all competition? Can the other functions of neural networks be controlled by the temporal structure of neuronal activity?

To clarify first question, we need to employ the simpler network model of the integrate-and-fire neurons, which is mathematically tractable. Moreover, this tractability is helpful to explore the possibility that the synchronous firing can control the other type of functions for neuronal information processing. The network architecture of our model for winner-take-all competition is as follows. Each integrate-and-fire neuron receives inhibitory connections from the other all neurons, which is the standard synaptic organization ensuring winner-take-all competition. We also assume that each neuron receives self-excitatory connection. This assumption is based on the fact that each neuron corresponds to one neuronal group like column. Thus, the self-excitatory connection represents the effect of the mutual excitatory connections within one column. In our simulations, we control two factors of external inputs; one is the input current strength and the other is the degree of synchrony. For the degree of synchrony of external inputs, we consider only two extreme cases; synchrony and asynchrony. Under these situations, we can derive the conditions to realize the stable control of winner-take-all competition. As a result, it is revealed that the presence of the appropriate self-excitatory connection facilitates the stable control of the competition. Furthermore, it is theoretically shown that this property is robust against the synaptic delay and the noisy synchronous firing.

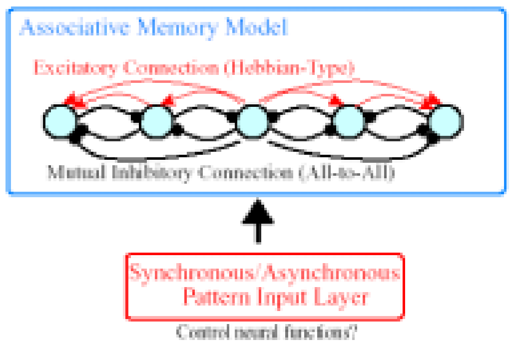

Figure 1 Model architecture in the network of associative memory model.

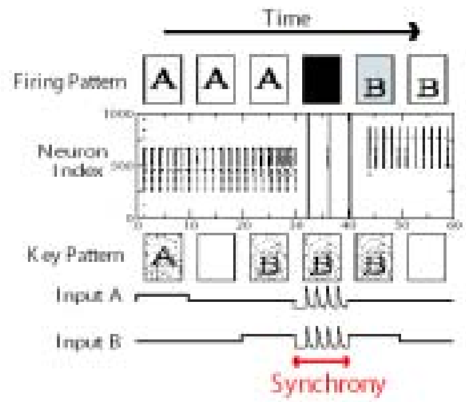

Figure 2 Role of synchronous firing in triggering the next retrieval in associative memory model

Next, to explore the possibility for the application to associative memory model, we developed and extended the above network model for winner-take-all competition. Figure 1 illustrates the network architecture for associative memory network. Instead of the self-excitatory connections, we assume mutual excitatory connections determined by some kind of learning rule like the typical Hebbian one. Figure 2 shows the typical behavior of this network in response to the synchrony-asynchrony transition of the external inputs. First, the pattern A was presented as the external input and the network retrieved the firing pattern A. In this case, the external input spike trains was assumed to be uncorrelated. This firing pattern remained without the input pattern A. Like the Hopfield type of neural network models, these behaviors reflect the nature of the associative memory function. However, even when the new pattern B was presented, the old firing pattern A remained stable. This is because the already firing neuron acquires more stability owing to the winner-take-all mechanism. Next, if the input spike trains synchronize, the winner-take-all mechanism was suppressed and the firing pattern A becomes unstable, leading finally to the synchronous oscillatory state in the network. When the input spike trains were returned to be uncorrelated again, the network exhibited the new firing pattern B in response to the presented one. Therefore, the synchrony-asynchrony transition of the external inputs plays a crucial role in triggering the change in the retrieval pattern whereas the input-firing pattern prepares the network for the next retrieval pattern. In addition, we numerically found that the same qualitative results hold for noisy synchronous firing inputs and higher storage level as well.

In this study, we address how the coherence of neuronal activity could affect the property of neural networks. Here, we present two examples: winner-take-all competition and associative memory function. In both cases, we show that the synchrony-asynchrony transition of external inputs play a key role in triggering the change from old state to new state. In particular, it is interesting that, in the case of associative memory model, the timing of the next retrieval can be controlled by such synchrony-asynchrony transition.

References:

1. E. D. Lumer (2000), Effects of Spike Timing on Winner-Take-All Competition in Model Cortical Circuits, Neural Comp. 12, 181-194.