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

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Abstract

To investigate how the temporal structure of neuronal activity 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 a network of integrate-and-fire neurons, we study their effect. The results show that uncorrelated discharge among neuronal inputs allows the standard winner-take-all competition, whereas synchronization of the neuronal inputs prevents it. In the case of the associative memory model, we find that the timing of the next retrieval can be controlled by such a synchrony-asynchrony transition of external inputs.

Key words: Temporal coding; Winner-take-all; Associative memory; Synchronization

1 Introduction

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 [1]. Another experiment shows that the degree of synchrony is frequently modulated by switching attention [2]. From these results, it is suggested that synchronous neuronal activity may play an important role in realizing the brain functions efficiently. Moreover, employing the temporal structure of neuronal spike trains is thought to be one potentially powerful information processing

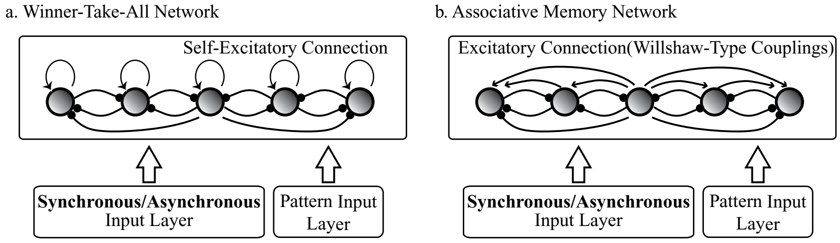

Fig. 1. **a** Schematic illustration of the winner-take-all competition model. Each neuron receives two external inputs, one from the asynchronous/synchronous input layer and one from the pattern input layer. **b** Network architecture of the associative memory model. Here, the self-excitatory connections of the winner-take-all model are replaced with the connections prescribed by the Hebbian-type learning rule.

strategy in neuronal systems. For example, one proposed possibility is that such synchronous activity constitutes the signal for the binding of different attributes of one object into a single perception. There have been many theoretical works studying synchronous neuronal activity. In most cases, they have focused on determining what dynamical mechanisms of neuronal systems can yield synchronous firing in networks [3,4]. Consequently, the understanding of synchronization in neuronal systems has progressed greatly [5–7]. However, there have been relatively few studies aimed at elucidating how such synchronous neuronal activitiy affects the function of neural networks, and the role of synchrony in the function of neural networks remains unclear.

We consider the effects of synchronous firing inputs on two typical functions of neural networks: winner-take-all competition and associative memory. The winner-take-all mechanism is very important for computational models of neural networks, because winner-take-all competition provides a general principle to construct biological feature maps in the brain [8–11]. Interestingly, a recent modelling study has revealed that the winner-take-all mechanism in neural circuits is remarkably sensitive to the timing of neuronal spike inputs [12]. It has been showed that uncorrelated discharge among neuronal inputs allows the usual winner-take-all competition, whereas synchronization of the neuronal inputs tends to prevent such competition. This suggests a possible role of such synchronization behavior in the functioning of real neuronal systems, for instance, in selecting information for the control of attention and voluntary motor action. From the theoretical point of view, however, the following two questions arise. First, what conditions are required to control winner-take-all competition? Second, can the other functions of neural networks, for example, associative memory, be controlled by the temporal structure of neuronal activity?

2 Model

In an attempt to answer the first question posed above, we employ a simple network model of integrate-and-fire neurons. The mathematical tractability of this model allows us to explore the possibility that synchronous firing can control various types 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 is cnnected to all other neurons and from these connections, it receives inhibitory inputs; this is the standard synaptic organization yielding winner-take-all competition. We also assume that each neuron possesses a self-excitatory connection. This assumption is based on the fact that each neuron can be regarded as representing a population of real neurons composing a single columnar structure.Thus, this self-excitatory connection represents the effect of mutual excitatory connections within one column. In our simulations, we have two controllable factors for the external inputs, the input current strength and the degree of synchrony. For the degree of synchrony of external inputs, we consider only two extreme cases, synchrony and asynchrony.

3 Simulation results

Figure 2 depicts shows a typical effect of synchronous input spikes on the properties of the winner-take-all network. The system was started with the condition that the 1st through 500th neurons receive a biased input from the pattern input layer. The current from the synchronous/asynchronous input layer was initially set in the asynchronous mode. Owing to the nature of the winner-take-all competition, only those neurons receiving a biased input are active (from the initial time, $t = 0$ to $t = 10$ msec). After the biased input is turned off, even when the remaining inactive neurons receive a larger biased input, this activity pattern is maintained (from $t = 10$ to $t = 30$ msec). However, when the current in the synchronous/asynchronous input layer is changed to the synchronous mode for a brief period, the existing firing pattern becomes unstable, and the network comes to exhibit a collective synchronized oscillatory state (from $t = 30$ to $t = 40$ msec). This result indicates that synchronous firing input tends to nullify the effect of the function of winner-take-all competition. After the asynchronous mode is recovered, a transition to a new pattern prepared by the pattern input layer takes place (from $t = 40$-$t = 60$ msec).

Next, to explore a similar application to the associative memory model, we developed and extended the above-described network model for winner-take-all competition. Figure 1 **b** illustrates the network architecture for the associative

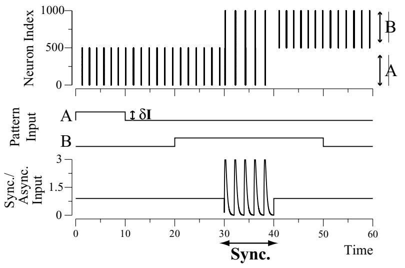

Fig. 2. Typical effect of synchronized spikes on winner-take-all competition. The top graph is a rastergram of the 1000 neurons composing the system. The middle and bottom graphs plot the time dependences of the input currents from the pattern input layer and the synchronous/asynchronous spike input layer, respectively. It is clearly seen that winner-take-all competition is suppressed by synchronized incoming spikes.

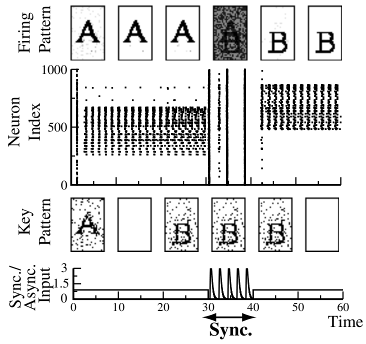

Fig. 3. A possible role of synchronized incoming spikes in controlling the function of associative memory. A transition of the retrieved pattern can be induced by switching the input spikes from asynchrony to synchrony and back to asynchrony.

memory network. In this case, instead of the self-excitatory connections, we assume mutual excitatory connections determined by some kind of learning rule, like the typical Hebbian one. Figure 3 displays the typical behavior of this network in response to the synchrony-asynchrony transition of the external inputs. First, a pattern A was presented as the external input, and the network retrieved the firing pattern A. In this case, the external input spike trains were assumed to be uncorrelated. This firing pattern was then found to remain after the input pattern A is stopped. As in the case of the Hopfield-type of neural network models, this behavior reflects the nature of the associative memory function. However, in the system we studied even when a new pattern B was presented, the old firing pattern A remained stable. This is because in the winner-take-all competition, the stablility of the firing state of a neuron that has been selected as a firing neuron (i.e. a "winner") is enhanced by the machanism of this competition. Next, we found that if the input spike trains are synchronized, the winner-take-all mechanism is suppressed, and the firing pattern A becomes unstable, leading finally to a synchronous oscillatory state in the network. Then, when the input spike trains were returned to the uncorrelated state, the network exhibited the new firing pattern B in response to its presentation. 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 found in futher numerical study that the same qualitative results hold for noisy synchronous firing inputs and a higher storage level as well.

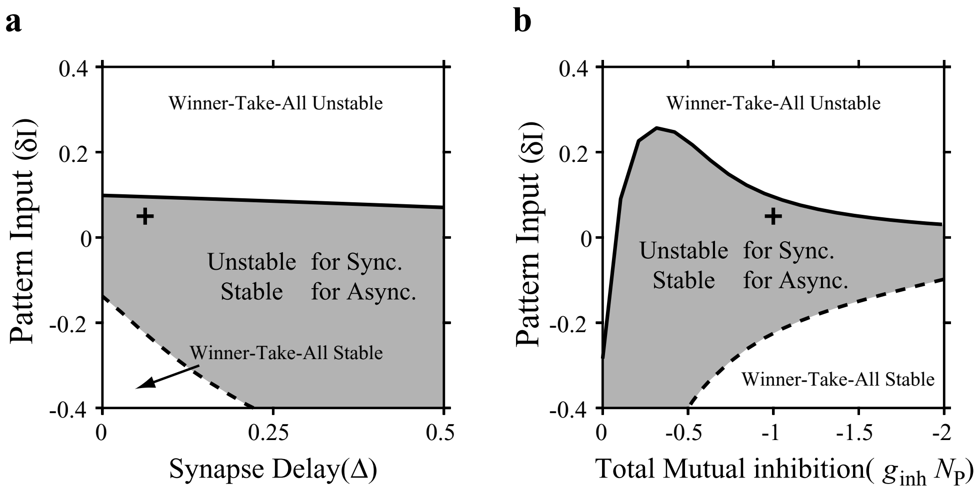

Fig. 4. Two parameter phase diagrams concerning the stability of the state selected through the winner-take-all competition. **a** The dependence of the stability on the total mutual inhibitory strength and the pattern input biased current. **b** The same as **a**, except that the horizontal axis corresponds to the synaptic input strength. The point corresponding the parameter values used in the simulations is indicated by the +. In the shaded region, a change in the stability of the winner-take-all state occurs in response to a synchrony-asynchrony transition in the sync/async input layer.

4 Theoretical analysis in the case of winner-take-all competition

In order to understand the result of the above numerical simulations, we analyzed the dynamical properties of the network. In the case of the winner-take-all network, we derived the conditions necessaryto realize stable control of winner-take-all competition. From this analysis, it is found that the property described above is insensitive to synaptic delay and the total mutual inhibitory strength (Figure 4). Furthermore, it is revealed that the presence of the appropriate self-excitatory connection facilitates the stable control of the competition (data not shown). A detailed analysis will be published elsewhere in the near future.

5 Conclusions

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

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