Propagation of quasi-stable activation in a chain of recurrent neural networks

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Abstract:

We introspectively guess that 'mental processes' are generation and extinction of images in a sequence. It is generally accepted that representation of an image in one's mind is caused by sustained activation of a neural population encoding this image. Mental processes can therefore be considered as transitions of quasi-stable neural activation from one neural population to another. Parallel recordings from the monkey cortex during a delayed GO/NO-GO task or the rest after a task performance support this view. We will show that stochastic dynamics of a chain of recurrent neural networks provides propagation of quasi-stable neural activation along the chain.

Introduction

It is generally viewed in cognitive neuroscience that representation of a certain image in one's mind is caused by reverberatory activation of a population of neurons that encode this image. Computational neuroscience tells that recurrent connection among a population of neurons can generate sustained activation of these neurons (Durstewitz et al., 2000; Wang, 2001). We introspectively guess that 'mental processes' evolve as consecutive generation and extinction of images in a sequence. By these considerations, we suppose that mental processes are expressed as transitions of quasi-stable neural activation from one population of recurrently connected neurons to another. Moreover, the time scale of mental processes is of the order ~hundred milliseconds to seconds. Therefore, quasi-stable activation of each population should last for duration ranging from hundred milliseconds to seconds, which is much longer than the time scale of neuronal spike generation (~milliseconds).

Several lines of neurophysiological evidence consistent with this view have been reported. Simultaneous neural ensemble recordings from the frontal cortex of a monkey during a delayed GO/NO-GO localization task have revealed that neuronal activity goes through sequence of quasi-stationary states during the delay period; each stationary states lasts for several hundred milliseconds (Abeles et al., 1995; Seidemann et al., 1995). This temporal sequence of neuronal activity probably reflects monkey's mental processes during the delay period. It has also been demonstrated that temporal patterns of neural activation during a task performance are reactivated in the monkey neocortex during the rest period after the task (Hoffman & McNaughton, 2002) or in the rat hippocampus during the REM sleep (Louie & Wilson, 2001); in both cases, the reactivation occurs at the same time scale as that for the task performance.

Hence there is a need to devise mechanisms that generate slow propagation of quasi-stable reverberatory activation of populations of neurons in a sequence. We will show that stochastic dynamics of a chain of populations of recurrently connected neurons can provide such mechanisms.

Model

We consider a set of recurrent networks of excitatory neurons. In each neuron of the network i projects to all neurons of the network $i+1$. Thus, a chain of feed-forward connections of recurrent networks is given (Fig. 1).

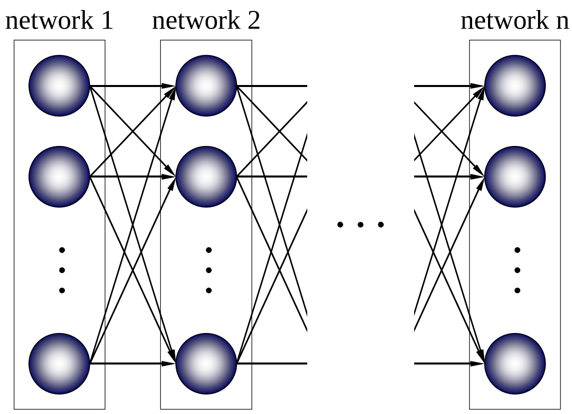

Fig. 1. Chain of feed-forward connections of recurrent neural networks. Recurrent connections within each network are not illustrated.

For the description of the membrane potential dynamics, the standard leaky-integrate-and-fire neuron model is used. The membrane potential is also subject to background stochastic noise.

One specific assumption is added: After a neuron sufficiently discharges, depolarization current is transiently induced in this neuron. This after-depolarization (ADP) current will make neuronal spiking more regenerative.

Results

Computer-simulation study is done to examine propagation of neural activation in the chain. The results obtained show that neural activation started at the network 1 slowly travels along the chain (Fig. 2). The activation of the network 1 is triggered by transient external stimulus given at time 0 (Fig. 2, red arrow), which is followed by sequence of spontaneous activation of the networks 2, 3, 4 and 5. Activation of each network can be said 'quasi-stable' because its temporal profile has a plateau period that lasts for several hundred milliseconds.

It can be verified that, for the quasi-stability and slow propagation of neural activation, the presence of background stochastic noise in combination with the ADP current is essential (data not shown, see Okamoto & Fukai, 2001).

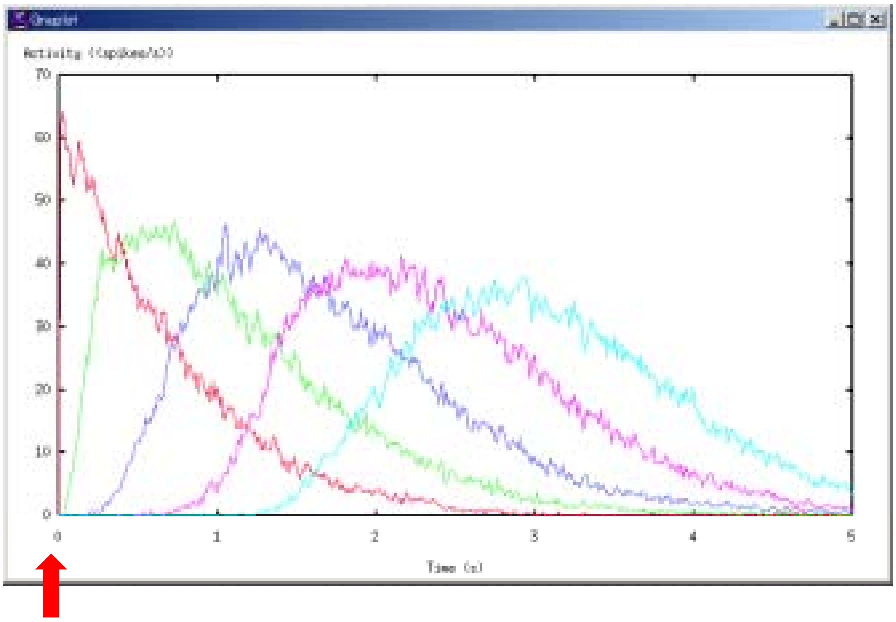

Fig. 2. Slow propagation of quasi-stable activation along the chain of recurrent networks. Red, green, blue, purple and light blue for networks 1, 2, 3, 4 and 5, respectively.

Discussion

We have shown that the stochastic dynamics of a chain of populations of recurrently connected leaky-integrate-and-fire neurons endowed with the ADP current produces slow propagation of quasi-stable neural activation along this chain. The results may suggest neural mechanisms underlying mental processes.

As seen in Fig. 1, the shape of the temporal profile of neural activation is more broadened for later networks in the chain. Introduction of inhibitory neurons, which are omitted in the above, seems to make the shapes uniform irrespective of the places of networks in the chain.

The structure of our model (Fig. 1) is closely similar to that of the synfire chain. However, there is an essential difference between them: Neurons in each layer in our model are recurrently connected, but those in the synfire chain are not. Because of this difference, the synfire chain yields the temporal profiles of neural activation that are quite contrast to those given by our model: In the synfire chain, synchronous spiking rapidly propagates along the chain with precise timing. Phenomena to be accounted for by the synfire chain and our model may be different.

Experimental prediction:

In our model, the timing of activation of each network largely fluctuates across trials. The time difference between activations of two different networks is of the order of hundred milliseconds to seconds. Therefore, activations of neurons belonging to different networks will give long time (~hundred milliseconds to seconds), broad cross-correlation. Experimental observation of such cross-correlation by pair-wise recordings will support our model.

References

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