Chapter 20
A Stochastic Resonance Memory Mechanism of Hippocampus

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Abstract Using the hippocampal cell channel model, the transmission features of hippocampal system are under the research. The process of memory is simulated by stochastic resonance. By synaptic model, the hippocampus model is constructed, which analyzes the summation of postsynaptic currents in the network. The strong capacity of spatiotemporal encoding in the network indicates the features of CA3 network during the information transmission process in the hippocampus. Analyzing the memory expression in CA1 under PP signal from entorhinal cortex or SC postsynaptic current respectively, results show that the reason is that single subthreshold signal cannot cause memory and stochastic resonance of them. The modeling result with time delay of the synaptic transmission is in accordance with the experimental phenomena of action potential in the hippocampus.

Keywords Hippocampus · stochastic resonance · memory pattern · ISI

Introduction

The function of noise was found first when Benzi explained some questions of ice age. The phenomenon that peak value appears when Signal-to-Noise (SNR) increases rapidly under certain strength of noise is named stochastic resonance [1]. Longtin pointed out that stochastic resonance is very important to neurophysiology and the noise plays a key role in neuron encoding [2, 3]. Outside signal accepted from the distal end of nerve is usually very weak when it reaches our brain, which can be strengthened by noise. A memory recognition process will be explained based on stochastic resonance.

For the hippocampus, Traub founded a simplification model with 19 pyramidal cells to describe the structure of CA3 in 1982 [4]. The result of this model shows that the bursting discharge of a pyramidal cell is very complicated, and that the

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number of cells considered is too less. Afterwards, Traub and Jeffyerses carried on an improvement over the original model, building up a CA3 network with 100 pyramidal cells [5]. The excitory synapse among pyramidal cells is random, which indicates that the strong synaptic connection is a necessary condition of the synchronous bursting discharges. In 1998, Tateno, Hayashi and Ishizuka further amplified cells scale to 256 pyramidal cells and 25 interneurons in a CA3 network [6], in which the influence of synaptic strength on action potential had been studied thoroughly in this model. In various models, CA3 is studied alone, or is investigated just with CA1; however, the influence of MF connection of DG upon CA3 is often neglected. This paper is concerned with perfecting the structure of system, adding DG network and EC's effects to the system and analyzing the memory process.

The Hippocampal Neuron Model

There are two kinds of cells in the hippocampus: excitory neurons (mainly granulosa cells in DG and pyramidal cells in CA1 and CA3) and inhibitory neurons (mainly interneurons in CA1, CA3 and DG). Generally, the following model is employed to describe excitory neurons:

$$\begin{aligned} C\frac{\mathrm{d}V}{\mathrm{d}t} &= g_{\mathrm{Na}}m^3h(V_{\mathrm{Na}}-V)+g_{\mathrm{Ca}}s^2r(V_{\mathrm{Ca}}-V)+g_{\mathrm{Ca(low)}}s_{\mathrm{low}}^2r_{\mathrm{low}}(V_{\mathrm{Ca}}-V)\\ &\quad+g_{\mathrm{K(DR)}}n(V_{\mathrm{K}}-V)+g_{\mathrm{K(A)}}ab(V_{\mathrm{K}}-V)+g_{\mathrm{K(AHP)}}q(V_{\mathrm{K}}-V)\\ &\quad+g_{\mathrm{K(C)}}c\,\min(1,\chi/250)(V_{\mathrm{K}}-V)+g_{\mathrm{L}}(V_{\mathrm{K}}-V)+g_{\mathrm{af}}(V_{\mathrm{syn(e)}}-V)\\ &\quad+I_{\mathrm{syn}}+I_{\mathrm{stim}} \end{aligned} \tag{20.1}$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \alpha_z(1-z)-\beta_z z, \quad z \text{ stands for } m, h, s, r, s_{\mathrm{low}}, r_{\mathrm{low}}, n, a, b, q, c \tag{20.2}$$

$$\frac{\mathrm{d}\chi}{\mathrm{d}t} = -\phi I_{\mathrm{Ca}}-\beta_\chi \chi \tag{20.3}$$

In addition to a large number of excitory neurons, there are a few interneurons in CA3 and DG. Despite its small proportion, interneurons play an important role in maintaining the equilibrium between excitation and inhibition in the hippocampus. The interneuron model can be described in the following way:

$$C\frac{\mathrm{d}V}{\mathrm{d}t} = g_{\mathrm{Na}}m^3h(V_{\mathrm{Na}}-V)+g_{\mathrm{K(DR)}}n^4(V_{\mathrm{K}}-V)+g_{\mathrm{L}}(V_{\mathrm{L}}-V)+I_{\mathrm{syn}} \tag{20.4}$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \alpha_z(1-z)-\beta_z z, \quad z \text{ stands for } m, h, n \tag{20.5}$$

Equations 4 and 5 can be adopted to describe the interneurons in the hippocampus. While neurons are connected by synaptic model, these models can analyze the nerve system of the hippocampus.

The Hippocampal Memory Model

The Introduction of Network and Synaptic Model

In order to analyze the system of the hippocampus, firstly a network structure should be constructed. For the sake of convenience, each pyramidal cell excites 8 pyramidal cells around in the network, and each interneuron inhibits 16 pyramidal cells around, which is subjected to the excitation from these 16 pyramidal cells. Hence, two adjacent interneurons together inhibit four common pyramidal cells (the shadows in Fig. 20.1a).

Here suppose DG has the similar network to CA3 (CA1), hence ○ in Fig. 20.1a indicates granulosa cells, and then a hippocampal network is attained in Fig. 20.1b. The cells form network by synaptic connection, which is given below. Each presynaptic action potential always causes an impulse of postsynaptic cells.
The impulse of postsynaptic cells is as follows.

$$I_{\text{syn}} = g_{\text{syn}}(V_{\text{syn}} - V) \tag{20.6}$$

$$g_{\text{syn}} = C_{\text{syn}}(\exp(-t/\tau_1) - \exp(-t/\tau_2)) \tag{20.7}$$

Stochastic Resonance Memory Recognition

A memory object "A" is considered. First it was accepted by cortex and converted into PP current signal which is input into the network of 16 × 16. For those neurons covered, $W_{\text{perep}} = 0.08$; otherwise, $W_{\text{perep}} = 0$. The potential of the neurons is indicated by the grey level from black to white, that is, near black means resting while near white firing.

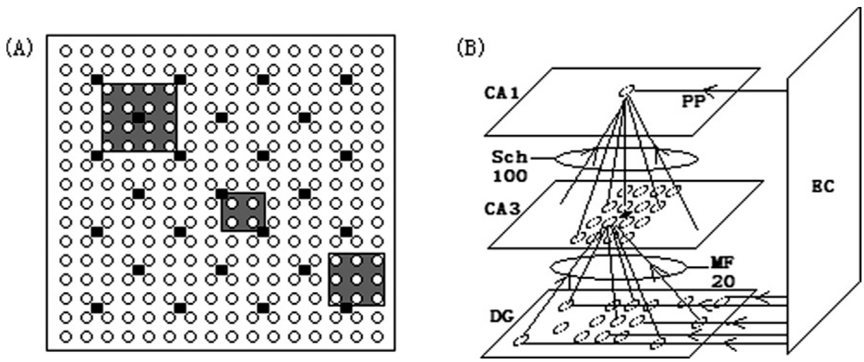

Fig. 20.1 (a) CA1, CA3 or DG network: 16 × 16.○: pyramidal cell or granulose cell. ■: interneuron. (b) hippocampus system structure. Each pyramidal cell in CA3 is exited by 20 granulose cells with MF connection. Each pyramidal cell in CA1 is exited by 100 pyramidal cells with SC connection. DG and CA1 are exited by PP signal

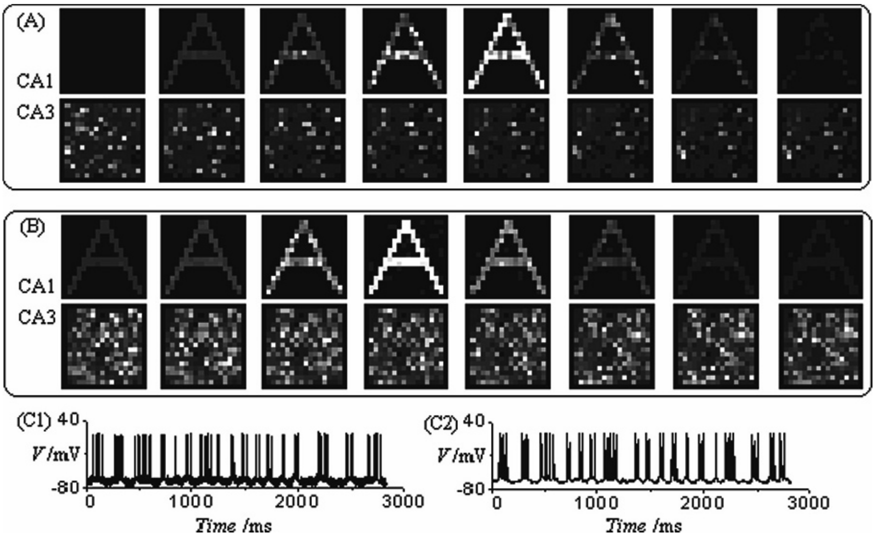

Fig. 20.2 (a) the incomplete memory pattern in the period of sparse pyramidal cells firing; (b) the complete memory pattern in the period of most pyramidal cells bursting synchronously; (C1) CA1 pyramidal cell fires under the incomplete memory pattern; (C2) CA1 pyramidal cell fires under the complete memory pattern

A complete hippocampal system memory is concerned. In Fig. 20.2, the memory is recalled under subthreshold PP signal and SC postsynaptic current in CA1, with the interval between two pictures 0.6 ms. CA3 in the second line is 1 ms ahead of CA1 because of the synaptic delay.

The neurons firing spontaneously are random in CA3-DG structure, and presynaptic neurons of SC connection are also random; therefore, SC postsynaptic current can be regarded as a random variable. Since noise with certain strength is applied into enlarging or detecting subthreshold signals, SC postsynaptic current can be considered as stochastic noise. Using stochastic resonance in the model, the PP subthreshold signal is strengthened by SC stochastic noise, and the memory object is recalled in CA1.

Discussion

A tentative study has been done on the memory mechanism of hippocampus. Memory, as a function, is explained by stochastic resonance. The recognition of a single letter “A” is simulated in the model, which is a relatively good memory expression. Obviously, memory objects in reality are far more complicated than a letter; as a result, in order to recognize complicated information, the input of PP signal should be more complicated, for instance, a word “MEMORY” as a memory object. Suppose the cortex of brain can decompose the object. When it is changed

Fig. 20.3 CA1 expression patterns when memory object is complicated signal "MEMORY"

into PP signal, the basic unit (letter) in this object is output in turn with the frequency of 50 Hz. By this, the memory result of CA1 is obtained (see Fig. 20.3).

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References

1. Benzi R., Sutera A., Vulpiani A.: The mechanism of stochastic resonance. J. Phys. A 14 (1981) 453–457.
2. Longtin Andre.: Autonomous stochastic resonance in bursting neurons. Phys. Rev. E 55 (1997) 868–876.
3. Collins J.J., Chow Carson C., Capela Ann C.: Aperiodic stochastic resonance. Phys. Rev. E 54 (1996) 5575–5584.
4. Traub R.D.: Simulation of intrinsic bursting in CA3 hippocampal neurons. Neuroscience 7 (1982) 1233–1242.
5. Traub R.D., Jefferys J.G.R.: Simulations of epileptiform activity in the hippocampal CA3 region in vitro. Hippocampus 4 (1994) 281–285.
6. Tateno K., Hayashi H., Ishizuka S.: Complexity of spatiotemporal activity of a neural network model which depends on the degree of synchronization. Neural Netw. 11 (1998) 985–1003.