Discussion on the Spike Train Recognition Mechanisms in Neural Circuits

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Abstract. The functions of neural system, such as learning, recognition and memory, are the emergences from the elementary dynamic mechanisms. To discuss how the dynamic mechanisms in the neurons and synapses work in the function of recognition, a dynamic neural circuit is designed. In the neural circuit, the information is expressed as the inter-spike intervals of the spike trains. The neural circuit with 5 neurons can recognize the inter-spike intervals in 5-15ms. A group of the neural circuits with 6 neurons recognize a spike train composed of three spikes. The dynamic neural mechanisms in the recognition processes are analyzed. The dynamic properties of the Hodgkin-Huxley neurons are the mechanism of the spike trains decomposition. Based on the dynamic synaptic transmission mechanisms, the synaptic delay times are diverse, which is the key mechanism in the inter-spike intervals recognition. The neural circuits in the group connect variously that every neuron can join in different circuits to recognize different inputs, which increases the information capacity of the neural circuit group.

Keywords: spike train, inter-spike intervals, response delay time, neural circuit.

1 Introduction

As a complex system, the functions of the neural system, such as learning, recognition and memory, are the emergences from the elementary dynamic mechanisms. Simulating by the complex networks is a common method to discuss the emergences from the complicated structure of the neural system. In the complex networks, the number of neurons could be as similar as in the neural system and the structure could be various[1]. We focus on the properties emerging from the complex structures, so the nodes and edges in the networks often have little dynamics. While in the real neural system, the neurons (the nodes) and the synapses (the edges) have plentiful dynamic mechanisms[2,3,4,5,6], which have

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been proved to be the substrate for the functions in brain, such as learning and memory[7,8,9]. To analyze these neural and synaptic dynamic mechanisms in large networks may be difficult, so that some simple neural circuits are developed to discuss the dynamic mechanisms in the neural system [10,11,12,13].

In the neural system, sensory systems present environmental information to central nervous system as sequences of action potentials or spikes. So it is considered that the information is expressed as the inter-spike intervals of the spikes [11,14,15,16,17]. In this paper, to discuss how the dynamic mechanisms in the neurons and synapses work in the recognition in the neural system, a neural circuit is designed to recognize the inter-spike intervals and the spike trains. Several dynamic neural and synaptic mechanisms are analyzed in the recognition.

2 Inter-spike Intervals Recognition

In the neural system, the environmental signals are expressed and transferred among the neurons as the type of spikes. When the input to a Hodgkin-Huxley neuron is a spike train composed of two spikes, the response property of the neuron will be of four kinds as follows:

(1)Responds to both of the spikes.
(2)Only responds to the first spike, but not responds to the second one. Because the neuron is in refractory period at the time of the second spike.
(3)Not responds to the first spike, but responds to the second one. Because under its parameters, at least two spikes could make the membrane potential of the neuron integrate to the threshold.
(4)Not responds to either of the spikes.

In details, the neurons satisfy the Hodgkin-Huxley equation[5],

$$C\frac{dV}{dt} = g_{Na}m^3h(E_{Na} - V) + g_K n^4(E_K - V) + g_L(E_L - V) + I_{syn} \tag{1}$$

in which V is the membrane potential. m, n, h are the gating variables, which satisfy $\frac{dX}{dt} = -(\alpha_X + \beta_X)X + \alpha_X$ for $X = m, h, n$. $\alpha_m = -0.1(25-V)/[\exp((25-V)/10) - 1]$, $\beta_m = 4\exp(-V/18)$, $\alpha_h = 0.07\exp(-V/20)$, $\beta_h = 1/[1+\exp((30-V)/10)]$, $\alpha_n = 0.01(10-V)/[\exp((10-V)/10)-1]$, $\beta_n = 0.125\exp(-V/80)$. The parameters are $C = 1\mu F/cm^2$, $E_{Na} = 120mV$, $E_K = -12mV$, $E_L = 10.6mV$, $g_{Na} = 120mS/cm^2$, $g_K = 36mS/cm^2$, $g_L = 0.3mS/cm^2$. $I_{syn}$is the synaptic current,

$$I_{syn} = \overline{g}_{syn}r(t)(V - E_{syn}) \tag{2}$$

where$\overline{g}_{syn}$is the maximal synaptic conductionit also shows the synaptic strength. $r(t)$ is the amount of neurotransmitter released from the pre-synapse, which is also the input signal here. Figure 1 shows that the responses of the neurons depend on the parameter of $\overline{g}_{syn}$ and the input inter-spike interval T. In the region 1, the neurons respond to both of the spikes. In the region 2, the neurons only respond to the first spike. In the region 3, the neurons only respond to the second spike. In the region 4, the neurons do not respond to either of the spikes.

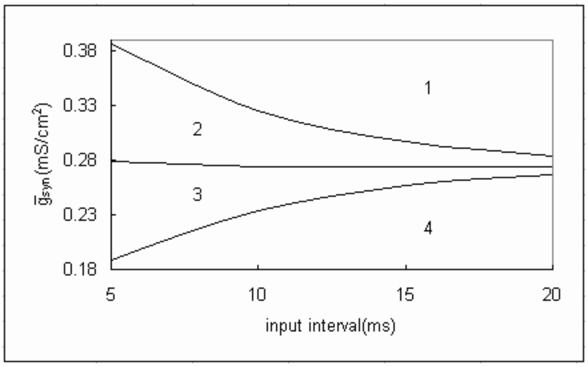

Fig. 1. The responses of the Hodgkin-Huxley neurons vary upon the $\overline{g}_{syn}$

Based on the characters above, a neural circuit is designed to recognize the inter-spike interval of the two input spikes (Fig.2). The circuit includes three layers. The first layer is the input neuron X, which fires two spikes as the input signal and the inter-spike interval is T_1. Suppose that the input spikes are at the time of t_0 and $t_1 = t_0 + T_1$. The second layer includes neurons α, β and γ. The input spikes from neuron X are transferred to the neurons α and γ through the synapses. The neuron α, with $\overline{g}^{\alpha}_{syn}$ in the region 2, only responds to the first spike (the spike at t_0) and the response delay time is τ_α. So the neuron α fires at the time of $t_\alpha = t_0 + \tau_\alpha$. The neuron γ, with $\overline{g}^{\gamma}_{syn}$ in the region 3, only responds to the second spike (the spike at t_1) and the response delay time is τ_γ. So the neuron γ fires at the time of $t_\gamma = t_1 + \tau_\gamma = t_0 + T_1 + \tau_\gamma$.The neuron β, with $\overline{g}^{\beta}_{syn}$ in the region 1, receives the spike from the neuron α and the response delay time is τ_β. So the neuron β fires at the time of $t_\beta = t_0 + \tau_\alpha + \tau_\beta$. The output layer neuron Y is a detect neuron, which receives the spikes from the neurons β and γ, and fires only when two spikes arrive within a time window of εms. Thus, when the neuron Y fires, means that $|t_\beta - t_\gamma| = |(\tau_\alpha + \tau_\beta) - (T_1 + \tau_\gamma)| < \varepsilon$.

The response delay times of the neurons α, β and γ are related with $\overline{g}^{\alpha}_{syn}$, $\overline{g}^{\beta}_{syn}$ and $\overline{g}^{\gamma}_{syn}$ that $\tau_\alpha = f_1(\overline{g}^{\alpha}_{syn})$, $\tau_\beta = f_1(\overline{g}^{\beta}_{syn})$, $\frac{df_1}{d\overline{g}_{syn}} < 0$, and $\tau_\gamma = f_2(\overline{g}^{\gamma}_{syn}, T)$, $\frac{\partial f_2}{\partial \overline{g}_{syn}} < 0$, $\frac{\partial f_2}{\partial T} > 0$. So when Y fires, it means the parameters $\overline{g}^{\alpha}_{syn}$, $\overline{g}^{\beta}_{syn}$ and

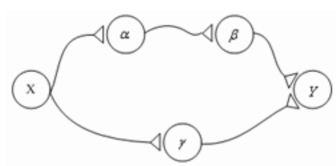

Fig. 2. The neural circuit structure for an inter-spike interval recognition

$\overline{g}_{syn}^{\gamma}$ in the neural circuit match the input interval T that $|t_\beta - t_\gamma| = |(\tau_\alpha + \tau_\beta) - (T_1 + \tau_\gamma)| < \varepsilon$, which equals to $|[f_1(\overline{g}_{syn}^{\alpha}) + f_1(\overline{g}_{syn}^{\beta})] - [T + f_2(\overline{g}_{syn}^{\gamma}, T)]| < \varepsilon$. Therefore, under different parameters of $\overline{g}_{syn}^{\alpha}$, $\overline{g}_{syn}^{\beta}$ and $\overline{g}_{syn}^{\gamma}$, the neural circuits could recognize the corresponding inter-spike intervals as $T \pm \varepsilon$.

However, a neural circuit recognizing only one inter-spike interval is not actual in the neural system. In fact, much experiments show that the neurons in brain join in different groups under different stimuli. As shown in Fig. 3, several neural circuits make up a large group. Not only the neurons $\alpha_i \rightarrow \beta_i$ and γ_i in the same circuit have an output neuron, but also the neurons $\alpha_i \rightarrow \beta_i$ and γ_j in different circuits connect to an output neuron. Such kind of structure optimizes the whole circuit group. For the delay times in different circuits are distributing in a wide range that any neurons $\alpha_i \rightarrow \beta_i$ and γ_j may combine to form a circuit, the whole circuit group can recognize the input intervals by choosing different circuit combinations. Thus, with the same number of neurons, the circuit group can process more information. For example, the group of 5 neural circuits may have 25 different combinations, which can recognize 25 different intervals.

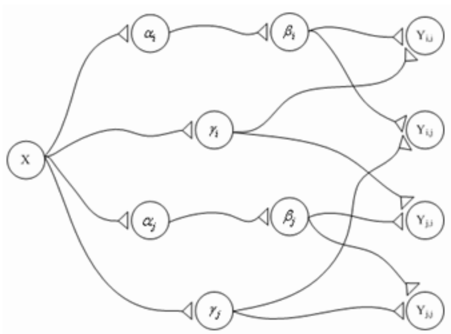

Fig. 3. The neural circuit group for inter-spike intervals recognition

Fig. 4 shows a group of 5 neural circuits recognizes the inter-spike intervals of 5ms, 10ms and 15ms. The vertical axis is the 25 output neurons. The dot, cross and circle express the corresponding neurons fire at that time, with dot for the fired neuron responding to the input interval of 5ms, and cross for 10ms, circle for 15ms respectively. As in Fig. 4, when the input inter-spike intervals are different, the circuit group would choose different circuit combinations to transfer the signals, and the output neurons would fire as different spatial patterns.

3 Spike Trains Recognition

Generally, a spike train includes several spikes and the information is expressed by a string of inter-spike intervals. A neural circuit is designed to recognize the spike train with more than one inter-spike interval (Fig. 5). Consider the simplest spike train including three spikes, with two inter-spike intervals of T_1 and T_2.

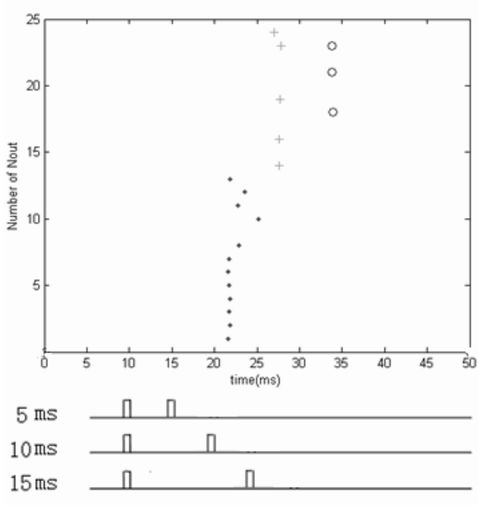

Fig. 4. Responding to the different input intervals, the output neurons fire as different spatial patterns

The circuit has three layers. The first layer is the input neuron X, which fires at t_0, $t_1 = t_0+T_1$ and $t_2 = t_1+T_2$. The second layer is composed of neurons α, β, γ and η. The input spikes from neuron X are transferred to the neurons α and γ through the synapses. The neuron α, with $\overline{g}^{\alpha}_{syn}$ in the region 2, only responds to the first and the third spikes (the spikes at t_0, and $t_2 = t_1+T_2$) and the response delay time are τ^0_α and τ^2_α . So the neuron α fires at the time of $t^1_\alpha = t_0 + \tau^0_\alpha$ and $t^2_\alpha = t_2 + \tau^2_\alpha$. The neuron β, with $\overline{g}^{\beta}_{syn}$ in the region 1, receive the spike from the neuron α and the response delay time is τ_β. So the neuron β fires at the time of $t^1_\beta = t_0 + \tau^0_\alpha + \tau_\beta$ and $t^2_\beta = t_2 + \tau^2_\alpha + \tau_\beta$. The neuron γ, with $\overline{g}^{\gamma}_{syn}$ in the region 3, only responds to the second spike (the spike at t_1) and the response delay time is τ_γ. So the neuron γ fires at the time of $t_\gamma = t_1 + \tau_\gamma$. The neuron η, with $\overline{g}^{\eta}_{syn}$ in the region 1, responds to all spikes from the neuron γ and the response delay time is τ_η. So the neuron η fires at the time of $t_\eta = t_1 + \tau_\gamma + \tau_\eta$.The output layer has two neurons Y^1 and Y^2, which are the detect neurons. Neuron Y^1 receives the spikes from the neurons β and γ, and fires when two spikes arrive within a time window of εms. Neuron Y^2 receives the spikes from the neurons α and η, and fires when two spikes arrive within a time window of εms.

As shown in Fig. 5, the neural circuit has two sub-circuits to transfer the input spike train. One sub-circuit is composed of the neurons α, β, γ and Y^1,which recognize the first inter-spike interval T_1 in the spike train. The other is sub-circuit is composed of the neurons γ, η, α and Y^2, which recognize the second inter-spike interval T_2 in the spike train. The structure of the two sub-circuits is same with the circuit in Fig. 2, and they have the same inter-spike interval recognition mechanisms. So the whole neural circuit of Fig. 5 can recognize a spike train with two inter-spike intervals. In details, the output

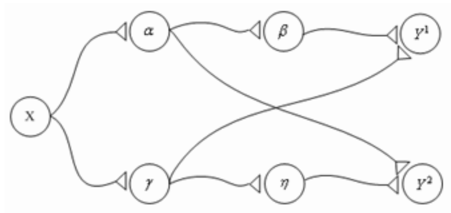

Fig. 5. The neural circuit structure for a spike train recognition

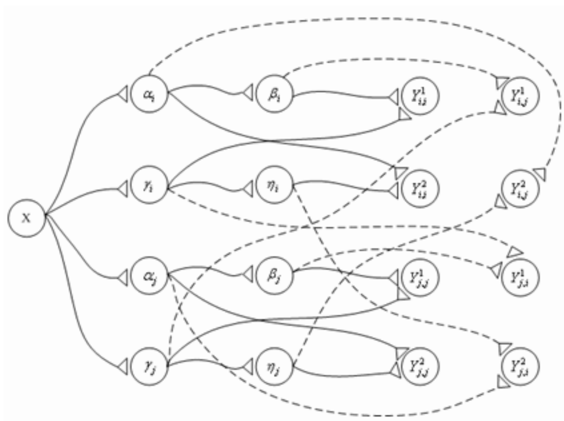

Fig. 6. The neural circuit group for spike trains recognition

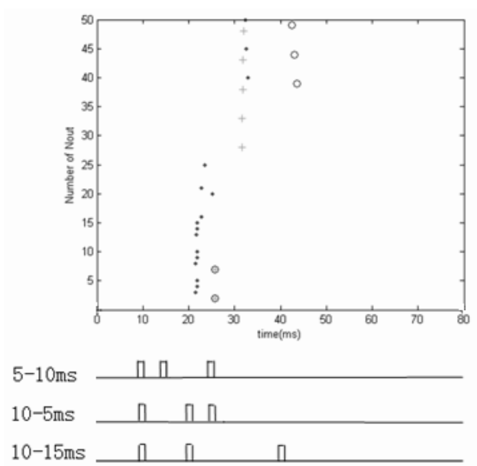

Fig. 7. Responding to the different spike trains, the output neurons fire as different spatial patterns

neuron Y^1 receives the spikes from the neuron β and the neuron γ at the times of t_β^1, t_β^2 and t_γ. Only when $|t_\beta^1 - t_\gamma| = |(\tau_\alpha^0 + \tau_\beta) - (T_1 + \tau_\gamma)| < \varepsilon$, the neuron Y^1 responds to fire. Similarly, the output neuron Y^2 receives the spikes from the neuron η and the neuron α at the times of t_η and t_α^1, t_α^2. Only when $|t_\eta - t_\alpha^2| = |(\tau_\gamma + \tau_\eta) - (T_2 + \tau_\alpha^2)| < \varepsilon$, the neuron Y^2 responds to fire. Thus, according to the output neurons Y^1 and Y^2 fire or not, the neural circuit recognizes whether the input spike train includes the inter-spike intervals of T^1 and T^2.

Several such neural circuits make up a large group. As shown in Fig. 6, not only the neurons $\alpha_i \to \beta_i$ and $\gamma_i \to \eta_i$ in the same circuit have the output neurons, but also the neurons $\alpha_i \to \beta_i$ and $\gamma_j \to \eta_j$ in different circuits connect the output neurons. Fig. 7 shows a group of 10 neural circuits with 50 output neurons recognizes three different spike trains.

The input spike trains are all composed of three spikes with inter-spike intervals of 5ms-10ms, 10ms-5ms and 10ms-15ms respectively. In Fig. 7, the vertical axis is the 50 output neurons. The dot, cross and circle express the corresponding neuron fires at that time, with dot for the neuron responding to the input spike train of 5ms-10ms, and cross for 10ms-5ms, circle for 10ms-15ms respectively. When the input spike trains are different, the circuit group chooses different circuits combinations to transfer the signals, and the corresponding output neurons fire. Therefore, the whole circuit group recognizes the input spike trains with the different output spatial patterns.

4 Conclusion

In this paper, the dynamic mechanisms in the neurons and the synapses in the learning and recognition are discussed. A neural circuit is designed to recognize the inter-spike intervals and the spike trains. There are several dynamic neural mechanisms in the recognition processes. When the input signal is a train of two spikes, the Hodgkin-Huxley neuron with dynamic synapses will response variously. With the different parameters, the response delay times are also different. Under this mechanism, the neural circuit with 5 neurons can recognize inter-spike intervals in 5-15ms. The synaptic delay time is one of the key variables in the recognition. Several neural circuits with 6 neurons make up a large group. The result shows that a group of neural circuits can recognize a spike train with three spikes. When the input signals are different, every neuron can join in different circuits and the output neurons form a spatial pattern. This structure increases the information capacity of the neural circuit, which is different with the common neural network. For the neural circuit here is still a small one, with no more than 50 neurons in each layer, the parameters and the number of neurons in the circuit are fixed. In the future work, a larger neural network will be developed, in which the parameters of neurons may be not fixed before the recognition.

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