Bistability of Synchronous and Desynchronous Dynamics in a Network with Gap Junctions

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Abstract

Recent physiological studies show a transient synchrony which means an alteration behaviour between synchronous and desynchronous states. These experimental findings and related theoretical studies have suggested that the importance of this kind of dynamics as bases of cognitive functions. However, an origin of this characteristic dynamics is still unclear. Here, we report that the transient activity can be realized in the network consisted of conductance-based model neurons with a bistability of firing and non-firing states. Neurons in this network are coupled with gap junctions which is a direct electrical connection with neighbor neurons. The bistability of the neuron play a key role to produce the transient dynamics of synchronous and desynchronous states.

Key words: Gap junction, bistability, neural coding, neural dynamics, chaotic itinerancy, synchronization.

1 Introduction

Recent experiments have revealed the transient dynamics between synchronous and desynchronous states, e.g., spiking patterns observed in rat inferior olive neurons show the alteration of rhythmic synchronous states and desynchronous states [1] , local field potential (LFP) data of an animal and electro encephalography (EEG) data of human [3] also exhibit the transient synchronous activity. Further, functions of this kind of dynamics have been investigated. The transient dynamics correlates with an attention and a perceptual binding, facilitates a synaptic plasticity, and coordinates a long-range interaction in the brain [2, 3] . Theoretical study have suggested that neural codes switch dynamically along with the state transition [4]. Little is known, however, about how the transient activity emerges in the neural systems.

Moreover, experiments have revealed the massive number of gap junctions in various region of the brain. These gap junctions are specialized areas of the cell membranes connecting neighbor cells; they induce synchronous firing [5]. In addition to the synchronous activity, theoretical studies suggest that gap junctions induce chaotic activities including the chaotic itinerancy [6, 7] . The chaotic itinerancy is one of possible scenarios to realize the transient dynamics between synchronous and desynchronous states in the network with gap junctions.

The purpose of this paper is to present an alternative scenario to produces the transient dynamics in the gap junction-coupled neural system, base on a characterization of the bistability of neuron. The paper is organized as following. First, in the next section, we show the conductance-based model with the bistability and a characteristics of their behaviours. After that, we construct the network with this neuron by connecting with gap junctions. In the third section, we show the result of computer simulation.

2 Model

Here, we describe the model mentioned in above. First, single neuron model is described in following subsection. After that, we construct the network consisted of this neuron and gap junctions.

2.1 Conductance based model with bistability

We used a simple two-variable conductance-based model, which is more plausible than a one-variable neuron model like the integrate-and-fire model, and is extracting the essential neural dynamics. [6, 8].

This model consists of two variables which are a membrane potential V and a potassium channel activation n [8].

$$C\frac{dV}{dt} = I(t) - g_L(V - E_L) - g_{Na}(V - E_{Na}) - g_K(V - E_K), \quad (1)$$

$$\tau_n \frac{dn}{dt} = n_\infty(V) - n, \quad (2)$$

$$m_\infty(V) = \frac{1}{1 + \exp\left[\frac{V_1 - V}{V_2}\right]}, \quad (3)$$

$$n_\infty(V) = \frac{1}{1 + \exp\left[\frac{V_3 - V}{V_4}\right]}. \quad (4)$$

The neuron is driven by the external input $I(t)$, the leaky current, the sodium current, and the potassium current. We chose following parameters to realize the bistable structure. We set $C = 31$ms, $\tau_n = 31$ms, the membrane conductances $g_L = 1$, $g_{Na} = 4$, $g_K = 4$, and corresponding reversal potentials $E_L = -78$ mV, $E_{Na} = 60$ mV, $E_K = -90$ mV. We use steady-state activation curves $m_\infty(V)$, and $n_\infty(V)$ with the slope factor $V_2 = 7$mV, $V_4 = 5$mV and parameters $V_1 = -30$ mV and $V_3 = -45$ mV satisfy $m_\infty(V_1) = n_\infty(V_3) = 0.5$.

Figure 1 shows the phase portrait to describes the geometric view of the model neuron. The model includes two attractors as shown in this figure. The first is a stable fixed point corresponding to the rest state. The other is a stable limit cycle with the action potential. The dashed curve in figure 1 indicates a unstable limit cycle. If the orbit starts inside of this region, the orbit converges to the stable fixed point. On the other hand, If the orbit starts outside of this region, the orbit makes the action potential and converges to the stable limit cycle. Figure 2 shows a time course of the membrane potential as a typical response of the neuron. This neuron takes two states of firing and non-firing even on same intensity inputs. These two states can be switched by fluctuating inputs (Fig 2 (b)).

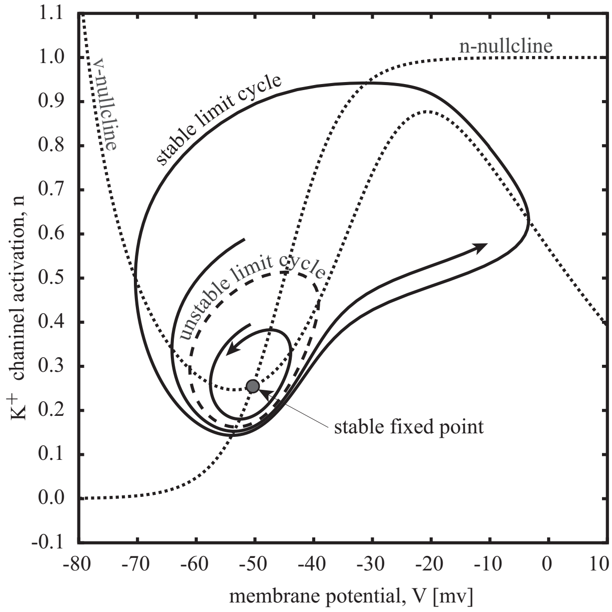

Figure 1: Phase portrait of the model neuron. Dotted curves indicate nullcline of V and n. The bold curve is the stable limit cycle. The point in the crossing of these nullclines is the stable fixed point. The dashed curve is unstable limit cycle. Curves with arrow indicate typical orbits of the model.

2.2 Network with gap junctions

The network with gap junctions and neurons specified in above is described as follows. We used two dimensional lattice network with 25 neurons as in figure 3.

$$C\frac{dV_i}{dt} = I_i(t) - g_L(V_i - E_L) - g_{Na}(V_i - E_{Na}) - g_K(V_i - E_K), \quad (5)$$

$$\tau_n \frac{dn_i}{dt} = n_\infty(V_i) - n_i, \quad (6)$$

$$(i = 1, \cdots, 25),$$

$$m_\infty(V) = \frac{1}{1 + \exp\left[\frac{V_1 - V}{V_2}\right]}, \quad (7)$$

$$n_\infty(V) = \frac{1}{1 + \exp\left[\frac{V_3 - V}{V_4}\right]}, \quad (8)$$

The i in the subscript of V, n, and $I(t)$ indicates the index of neurons. We used 25 neurons in this network, therefore, the i takes an integer of from 1 to 25.

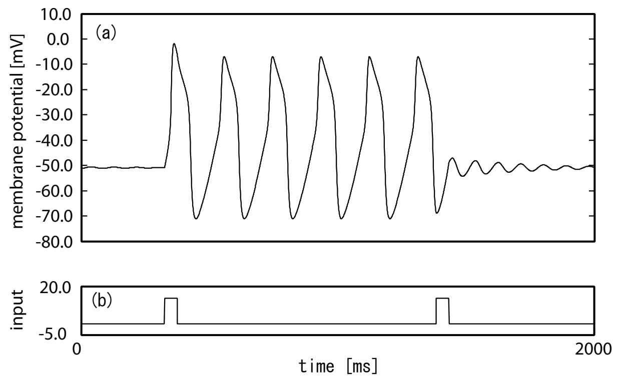

Figure 2: The typical response of the conductance-based model with bistable structure. The time course of the membrane potential (a) and the fluctuating input (b) are shown. The firing state as in the middle part of (a) and the rest states as in the both end of (a)are corresponding to the stable limit cycle and the stable fixed point in figure 1 respectively. These two states can be switched by the fluctuating input.

$I_i(t)$ is a current induced by external inputs and gap junctions, and is consisted of three terms:

$$I_i(t) = I_0 + \xi_i(t) + g_E \sum_{j}^{neighbors} (V_j(t) - V_i(t)). \quad (9)$$

The first term I_0 specify a constant input. The second term is a Gaussian noise $\xi_i(t)$ that is individually applied to each neuron with the strength D. The third is the current induced by the gap junction with the conductance g_E. Each neuron coupled with nearest neurons as in figure 3. We assumed the conductance g_E are uniform for all gap junction connections.

3 Simulation Results

Figure 4 shows the typical response of this model. We can observe the transient activity between synchronous and desynchronous states. In the synchronous states, we can also see the rhythmic firing with a period of about 180 ms. The period is corresponding to the period of the stable limit cycle of the neuron. In the desynchronous states, the firing frequency is low and that spike timing are almost irregular.

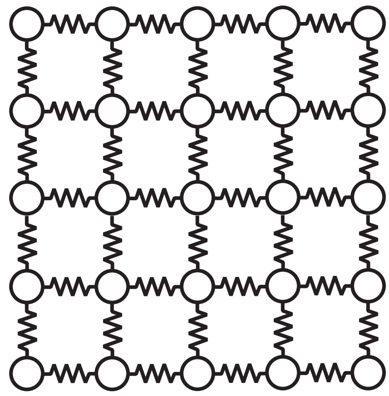

Figure 3: The structure of the network. The network is consisted of 25 neurons described in the body of this paper. Each neuron is connected with nearest neurons. The coupling strength of gap junction are uniform and specified by g_E.

The key mechanism of the alteration of these two states originate in the bistability of the conductance-based model as you see in the figure 1. The orbit of each neuron coupled with gap junctions attracts each other. Consequently, the orbits of these neurons tend to stay in one side of two attractors. In the synchronous states, the orbits stay on the stable limit cycle. In the desynchronous states, almost of these orbits trap each other near the stable fixed point. The fluctuating noise allows to escapes from this region and make the desynchronous spiking. If a certain amount of neurons fire in short time period, the state can change to the synchronous state.

4 Conclusion

In this paper, we have shown that the transient dynamics of synchronous and desynchronous states can be realized in the network consisted of bistabe type neurons and gap junction connections.

The model examined here may play an important role for the information coding in the brain , and cognitive roles mentioned in the introduction.

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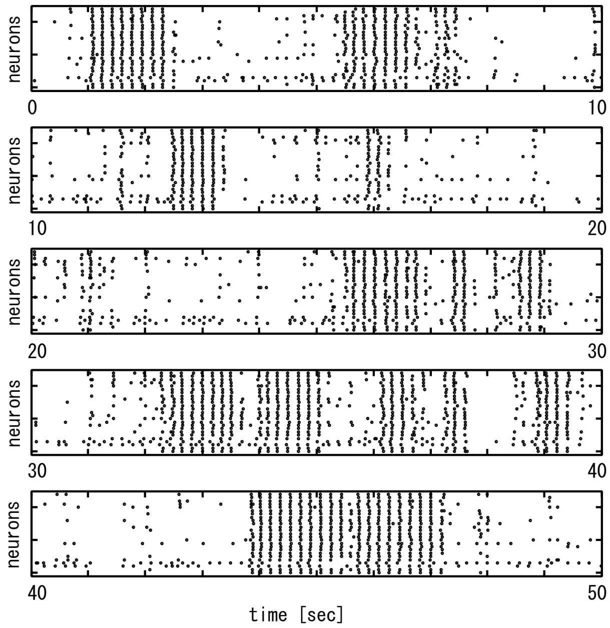

Figure 4: The typical response of 25 neurons in this model as a raster plot on the time from 0 to 50 s. Vertical axes of each plot show the index of neurons. Each dot in these plot indicate the timing of the spiking.

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