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Collective response, synapse coupling and field coupling in neuronal network

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ABSTRACT

Based on an improved neuron model with electromagnetic induction, the collective responses of chain neuronal network are detected. Besides the gap junction coupling between adjacent neurons, magnetic flux coupling is used to describe the effect of field coupling among all neurons. A statistical factor of synchronization is calculated to find the pattern stability dependence on the coupling intensity of junction coupling and field coupling. Bifurcation analysis and wave propagation are presented. It is found that signal propagation can be suppressed by field coupling on the network driven by external stimulus with diversity. Otherwise, network synchronization can be enhanced when external current stimulus are imposed on neurons of the network uniformly.

1. Introduction

Continuous exchange of sodium, potassium, calcium across the membrane via ion channels contributes to the ions flow and fluctuation of membrane potential, and appropriate external stimulus is helpful to trigger action potential since signal can propagate via synapse coupling. Based on biological experimental data, reliable neuron models are available for dynamical analysis and prediction for mode transition in electrical activities. In the last decades, many neuron models [1–5] have been proposed to produce the main properties in electrical activities by setting appropriate parameters value. Indeed, model setting should consider many physical and biological factors. For example, astrocyte [6–8] can participate in synaptic transmission by modulating and responding to the release of neurotransmitters with calcium elevations, and then the electrical activities of neurons can be modulated. On the other hand, autapse connection can enhance the self-adaption of neurons to external stimulus; the potential mechanism could be that delayed feedback is triggered via a close loop [9–13]. Appropriate distribution for autapse connection in the network can generate pacemaker and then the network can be occupied by continuous ordered waves such as stable pulse and wave fronts [14–16]. These pacemakers can excite the quiescent neurons in the network when autapse is applied with positive feedback type, while negative feedback in the autapse will generate defects [17], which block the wave propagation in the network. Furthermore, Wang et al. [18] argued that the formation mechanism for autapse connection could result from the injury of neuron axon, and thus auxiliary loop is developed to bridge the injured area [19]. Based on these theoretical neuron models, the synchronization stability [20,21], and the pattern selection under spatial coherence resonance have been extensively investigated [22–28] on the neuronal network by applying different connection types. For a brief view, readers can refer to [29,30]. Indeed, neuron can be regarded us effective signal processor, and neuronal network can be used as collection of a large number of signal processors that the media can encode the information completely. As a result, it could be helpful to detect weak signal under stochastic resonance, for example, Guo et al. [31] detected the response of neural systems to the weak envelope modulation signal, which is superimposed by two periodic signals with different frequencies. They confirmed that stochastic resonance occurred at the beat frequency in neural systems at the single-neuron as well as the population level, and the performance of this frequency-difference-dependent stochastic resonance is influenced by both the beat frequency and the two forcing frequencies. Both propagation time delay and intrinsic response time delay play important role in regulating the mode selection and dynamical response in electrical activities, and excitability diversity occurs in neurons. Therefore, chimera states [32] on network and phase synchronization [33] than complete synchronization become much attractive when partial time delay, diversity in coupling topology

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and excitability are considered. Readers can find guidance about chimera states theory in the review [34], which is in interest to collective behavior in neuronal network.

As well known, external forcing current can change the excitability of neurons and the modes in electrical activities can be changed from spiking to bursting, even with appearance of chaotic states. In realistic physical circumstance, exposure to electromagnetic radiation can affect the electrical activities of neurons and even the health of animals. For example, Thornton et al. [35] found that intense time-varying electromagnetic fields can generate modification on growth of mirror neurons**,** and the injury in this neuron could be associated with appearance of infantile autism. Vangelova et al. [36] confirmed that systolic and diastolic blood pressure of heart and Lipoprotein density could be beyond the normal value of healthy people when staffs are exposed to electromagnetic radiation in long time. As a result, disorder of glucose and lipid metabolism, and hypertension occur. Extensive evidences [37–39] indicate that cognition impairment can be induced when animals are exposed to high intensity electromagnetic radiation for a long period. For example, cell phone radiation can affect the central nerve system and can cause a decrease in neuron numbers [40,41] and a reduction of Phosphorylated synapsin [42] when the nerve system absorbs large energy from electromagnetic fields. Yi et al. [43,44] confirmed that electrical activities of neurons can be modulated by an external field. Chen and Li et al. [45, 46] suggested that an equivalent loop current can be imposed on the neuron model and the firing patterns can be controlled. Gu et al. [47] proposed biological verification on bifurcation behaviors from theoretical neuron models. To confirm the emergence of multiple modes in electrical activities, Lv et al. [48,49] suggested that magnetic flux can be used to describe the effect of electromagnetic induction and radiation on neuronal activities. Inspired by the contribution in Ref. [48], Wu et al. [50,51] presented an improved cardiac tissue model, and explained the death mechanism of heart subjected to the electromagnetic radiation. Furthermore, Wang et al. [52,53] discussed the dynamical response of neurons in presence of electromagnetic radiation, and synchronization approach under electromagnetic radiation are also discussed in Refs. [54,55]. Neuronal networks [56] can be helpful to understand the occurrence of collective behaviors for neurons.

In this paper, based on the proposed neuron model [48,49], chain network is approached by considering the gap junction coupling and field coupling, which is described by magnetic flux associated with magnetic field. The collective behavior, synchronization and pattern formation will be discussed.

2. Model and scheme

The dynamical equations for the network under field coupling, whose local kinetics is described by the improved Hindmarsh–Rose neuron model [48,49] with the effect of the electromagnetic induction, are

$$\begin{cases} \dot{x}_i = y_i - a{x_i}^3 + b{x_i}^2 - z_i + I_{ext} + D_1(x_{i+1} + x_{i-1} - 2x_i) - k_1\rho(\varphi_i)x_i \\ \dot{y}_i = c - d{x_i}^2 - y_i \\ \dot{z}_i = r[s(x_i + 1.6) - z_i] \\ \dot{\varphi}_i = 0.9x_i - 0.5\varphi_i - D\sum\limits_{\substack{j=1 \\ j\neq i}}^{N}(\varphi_j - \varphi_i) \end{cases} \tag{1}$$

where *x, y, z, φ* denotes the membrane potential, slow current for recovery variable, adaption current and magnetic flux across the membrane potential, respectively. I_{ext} represents external stimulus, $k_1\rho(\varphi)x$ the induction current, the memductance $\rho(\varphi) = \alpha + 3\beta\varphi^2$ is calculated for memristor, the subscript *i* describes the node position in the network. D_1 defines the coupling intensity via gap junction between neurons; *D* represents the intensity of field coupling. The same parameters value are set to $a = 1$, $\mathrm{b} = 3$, $\mathrm{c} = 1$, $\mathrm{d} = 5$, $r = 0.006$, $\mathrm{s} = 4$, $\alpha = 0.4$, $\beta = 0.02$. The external forcing current is fixed at appropriate values to observe phase transition in electrical activities. Based on mean field theory, a statistical factor of synchronization *R* is defined as follows.

$$\begin{cases} \mathrm{F} = \frac{1}{\mathrm{N}}\sum\limits_{i=1}^{N} x_i \\ \mathrm{R} = \dfrac{<\mathrm{F}^2> - <\mathrm{F}>^2}{\frac{1}{N}\sum\limits_{i=1}^{N}\left(<{x_i}^2> - <x_\mathrm{i}>^2\right)} \end{cases} \tag{2}$$

where $<*>$ indicates the average of a variable over time, *N* is the number of the neurons. Perfect synchronization will be obtained on the network at $R\sim1$, while $R\sim0$ determines emergence of ordered spatial distribution and spatial pattern, non-perfect synchronization is obtained. $N = 100$ will be used for the following numerical analysis.

3. Numerical results and discussion

In this section, the fourth-order Runge–Kutta algorithm is used with time setp $h = 0.01$. The network is treated with no-flux boundary condition, and the transient period is about 2000 time units. The initial setting is selected with different values depended on the node position. $x_i = 3$, $y_i = 0.3$, $z_i = 0.1$, $\varphi_i = 1 + 0.1{*}i$, where *i* is the node position in the chain network. To discern the effect of magnetic induction and field coupling, subthreshold stimulus is applied as $I_{ext} = 1.1$. The time evolution of membrane potentials of all neurons in the network is calculated to observe the snapshots for spatial pattern, and sampled time series for the membrane potential of neuron (node $i = 50$) are calculated to explore the mode transition. At first, adjacent coupling intensity is fixed by setting $D_1 = 0.5$, $k_1 = 1.0$. Then the intensity of field coupling is changed to observe the sampled time series for membrane potential, see Fig. 1, and wave propagation is plotted in Fig. 2.

The results in Fig. 1 confirm that quiescent neurons can be activated to trigger bursting by appropriate field coupling even when subthreshold forcing current is applied to the neurons. As well known, subthreshold stimulus can't excite quiescent neurons, while neuron can be activated by applying larger intensity of forcing current beyond the threshold about $I_{ext} = 1.2$. However, the electrical activities can also be suppressed by further increasing the intensity of field coupling. Also, the evolution of collective behaviors of membrane potentials are calculated and shown in Fig. 2.

The results in Fig. 2 confirmed that continuous wave fronts can be induced and field coupling can enhance the synchronization behaviors. By further increasing the intensity of field coupling, wave propagation is suppressed and the network is under homogeneous which all neurons become quiescent completely. The feedback gain k_1 describes the contribution of electromagnetic induction on membrane potential by generating induction current. To discern the effect of induction current on mode selection in electrical activities, the coupling intensity between neurons is fixed at $D_1 = 0.5$, field coupling via magnetic flux is selected as $D = 0.001$, then the feedback gain is adjusted to observe the response in electrical activities and wave propagation. The results are shown in Figs. 3 and 4.

When the coupling intensity is fixed, the spiking state can be suppressed by further increasing the feedback gain so that the effect of the electromagnetic induction is enhanced, and the neuronal activities are controlled to become periodical firing. As a result, the network synchronization is set up. In Fig. 4, the spatiotemporal patterns are plotted to estimate the synchronization dependence on the induction current.

That is, periodical oscillation in electrical activities can enhance the synchronization of network. Furthermore, stronger induction