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Application of complex network method to spatiotemporal patterns in a neuronal network

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HIGHLIGHTS

- Using complex network method to characterize the spatiotemporal patterns.
- The spiral wave induces higher network synchronization compared to plane wave.
- The spiral wave contributes to neural information transmission and strengthens the functional integration compared to plane wave.

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ABSTRACT

Spiral waves have been found to appear alternatively with plane waves in the brain cerebral cortex, which has a significant effect on neuron firing behaviors. In this paper, we propose a functional firing network based on the correlated firing behaviors among neuronal populations and use the complex network method to investigate the effects of spiral waves and plane waves on the structure and function of the network. We first analyze the correlation coefficient and the largest eigenvalue of the functional firing network. We find a larger range distribution of correlation coefficients and greater largest eigenvalue of the functional firing network for spiral waves than those for plane waves, which indicates that spiral waves induce higher network synchronization. In addition, we explore the topological structure of the functional firing network using the complex network method. We find that the functional firing network for spiral waves has a larger degree and global efficiency and a lower modularity and characteristic path length than that for plane waves, revealing that spiral waves contribute to neural information transmission and strengthen the functional integration. Our work not only provides new insights for studying spatiotemporal patterns, but is also helpful for explaining the modulation of spiral waves on brain function.

1. Introduction

Spatiotemporal patterns have received considerable attention in recent years due to their certain and potential functions for the nervous system [1,2], and such patterns reflect much information about the dynamical behavior of neurons and neural

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networks. The spiral wave is a type of special spatiotemporal pattern and has been observed in turtle visual cortex [3], rat neocortical slices [4] and intact mammalian cortex [2]. Generally, spiral waves have a short life span and alternately appear with plane waves in biological experiments, but spiral waves with a long life span are related to brain disorders, such as epileptic seizures [2]. Therefore, the exploration of spiral waves contributes to our understanding of the modulation of spiral waves on neural information transmission and brain function.

It is well known that the spatiotemporal pattern is a type of synchronous firing of neurons that has a significant effect on the collective behavior of neurons [2,4–9]. Biological experiments found that electroencephalogram (EEG) data collected from the experimental cortex showed an abruptly decreased oscillation amplitude and increased frequency when a spiral wave appears, which indicates that spiral waves can modulate cortical activities by decreasing the oscillation amplitudes and increasing the oscillation frequencies of neurons around the spiral tip [2,4]. Furthermore, spiral waves are closely connected to the spatial coherence resonances and network synchronization [1,10–14]. For example, coherence resonances occur when spiral waves appear [13], and the corresponding firing synchronization degree of neurons is often high in neuronal networks [12,14]. However, because of the complex interactions between different neurons, the current method is not sufficient for accurately and thoroughly characterizing the effect of spiral waves on neural information transmission and brain function. For example, it is still unknown how spiral waves contribute to normal and abnormal neural information transmission among brain local regions by modulating the firing frequency and amplitude of neurons around the spiral tip. Therefore, a more subtle method based on the interconnection among neurons is needed to reveal the intrinsic role of spiral waves on neural information transmission and brain function.

The fluctuations in the firing activity of neurons are correlated under different brain states, such as the sensory and motor input states [15–18]. Recent experiments have found that the firing correlation can be altered when the brain is in different states. For example, the brain signals recorded from the primate visual cortex showed that the attention or task stimulation caused the correlation structure to change [15,19,20] and induced a low magnitude of correlation [21]. Moreover, the decrease of firing correlation is accompanied by brain state desynchronizing [16,17,22,23], and a transient decrease in firing correlation is often followed by stimulus onset [23–25,18]. At the macroscopic level, the firing correlation between different brain regions containing millions of neurons, which is called the functional connection, is used to construct the functional brain network [26]. At the microscopic level, the firing correlation between different neurons has been used to analyze the neuronal population coherence [27]. Based on the firing correlation between different neuronal populations in a neuronal network, a new network can be extracted, which is called a functional firing network. The functional firing network considers the functional connection among neuronal populations rather than the synaptic connection, the advantage of which is that it neglects how a specific spatiotemporal pattern forms but strengthens the effect of a specific pattern on interconnection among neuronal populations. Therefore, this type of network provides more information about the effect of spatiotemporal patterns on neural information transmission among neuronal populations.

Many analysis methods have recently been proposed for investigating the topological properties of complex networks, such as the complex network method [28–30], random matrix theory (RMT) [31] and principal component analysis (PCA) [32]. The complex network method based on graph theory is the most widely used method for characterizing the topological structural properties of all types of complex networks, such as functional and structural brain networks [29,28,33,34], neural networks [35], social networks [36,37], biological networks [37], and so forth [38,39]. Thus, using the complex network method to characterize the functional firing network is more helpful for revealing the modulation of specific spatiotemporal patterns on interconnections among neuronal populations.

In this paper, we construct the functional firing network based on the firing correlation between neuronal populations while different spatiotemporal patterns appear in the neuronal network to investigate the modulation of spiral waves on the network structure and function. We first study the effect of spatiotemporal patterns on the firing synchronization of neuronal populations, and then we use the complex network analysis method to explore the topological structure of the functional firing network. Our results show that the spiral wave induces higher synchronization of the functional firing network, makes the functional firing network denser, and promotes the neural information transmission more efficiently.

2. Neuronal network model and methodology

2.1. Neuronal network model

The neurons are described by the Hodgkin–Huxley model and embedded in a two-dimensional square lattice, in which a neuron is only connected to its four nearest-neighbor neurons through electrical synapses. The neuronal network model is described as follows [40]:

$$\begin{aligned} C_m \frac{\mathrm{d}V_{i,j}}{\mathrm{d}t} = &- g_{Na} m_{i,j}^3 h_{i,j} (V_{i,j} - V_{Na}) - g_L (V_{i,j} - V_L) \\ &- g_K n_{i,j}^4 (V_{i,j} - V_K) + I_{ext} + D(V_{i,j+1} + V_{i,j-1} + V_{i+1,j} + V_{i-1,j} - 4V_{i,j}), \end{aligned} \tag{1}$$

where (i, j) and (k, l) represent the locations of neurons and V_{ij} is the membrane potential of the neuron located on (i, j). C_m is the membrane capacitance; g_{Na}, g_L and g_K are the sodium, leakage and potassium conductances, respectively; and V_{Na}, V_L, and V_K are the corresponding reversal potentials. I_{ext} is the applied current, and D is the coupling strength.