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Random coupling strength-induced synchronization transitions in neuronal network with delayed electrical and chemical coupling

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HIGHLIGHTS

- Random coupling strength induced synchronization transitions in neuronal network.
- Enhancement of synchronization transitions by proper time delay.
- Stronger synchronization transitions for chemical coupling than for electrical coupling.
- Optimization of synchronization transitions by network average degree.

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ABSTRACT

Regulating the coupling strength of neurons by noise, we numerically study the effect of the fluctuation of coupling strength on the synchronization of scale-free neuronal network with time delays. It is found that the neurons exhibit synchronization transitions when noise intensity is varied, and the synchronization transitions are delay-dependent and are enhanced at certain time delays. This phenomenon becomes stronger for chemical coupling than for electrical coupling. As network average degree increases, this phenomenon decreases monotonically for electrical coupling. However, for chemical coupling there is an optimal network average degree at which the phenomenon becomes strongest. These results show that the fluctuation of coupling strength can induce different synchronization transitions in scale-free neuronal network. This implies that random coupling strength could play a crucial role in the information transmission in neural systems.

1. Introduction

Synchronization processes are ubiquitous in nature and play a very important role in many different fields such as physics, chemistry, ecology, sociology and biology. Synchronization phenomenon has been extensively studied in nonlinear dynamical systems, particularly complex networks [1,2]. It is shown experimentally that synchronization can occur in many special areas of the brain, such as the olfactory system or the hippocampal region [3–5], and synchronous activity is considered to be related with several neurological diseases such as epilepsy and tremor in Parkinson's disease [6,7]. In recent decade, some novel synchronization phenomena have been observed in neuronal systems [8–20], such as electrical coupling-enhanced synchronization in coupled bursting neurons [10], diffusive coupling enhanced synchronization in small-world network of spiking neurons [12], subthreshold stimulus-enhanced synchronization in a square lattice noisy neuronal network [13]; time

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delay induced synchronization in coupled neurons and neuronal networks [14–20]; noise induced or enhanced synchronization in excitable media [21], coupled thermosensitive neurons [22], human-brain activity [23], and scale-free Morris–Lecar neuron networks [24].

In recent years, synchronization transitions induced by time delay and coupling strength have been observed in neuronal networks. For example, coupling strength can induce synchronization transitions in scale-free bursting neuron network [25] and intra- and inter-neuronal coupling can induce synchronization transitions in a neuronal network of sub-networks [26]. Time delay can induce synchronization transitions in two coupled fast spiking neurons [27] and small-world neuronal networks [28,29] as well as scale-free neuronal networks [25,30–32]. More recently, noise-induced synchronization transitions have also been observed in scale-free thermosensitive neuron network with delayed electrical or chemical coupling [33]. However, these studies have only dealt with neuronal networks with fixed coupling strength.

It is known that neuronal coupling is always changing due to synaptic plasticity, and particularly it may fluctuate and randomly changes under the regulation of noise arising from stochastic dynamics of synapses and ion channels. Therefore, it is of significance to study the synchronization of neuronal networks with random coupling strength.

In this paper, by regulating the coupling strength of neurons by noise, we study the effect of the fluctuation of coupling strength on the synchronization of delayed scale-free thermo-sensitive neuron network with electrical or chemical coupling. First, we present time delay induced synchronization transitions when coupling strength is fixed. Second, we study how the fluctuation of coupling strength induces synchronization transitions. Third, we discuss the effects of network average degree and coupling strength on the synchronization transitions and compare the results for electrical and chemical coupling. Meanwhile, mechanism is briefly analyzed. Finally, conclusion is given.

2. Model and equations

The model used is modified Hodgkin–Huxley (MHH) neuron proposed by Braun et al. to describe the firing dynamics of thermo-sensitive neurons [34]. This model can exhibit different temperature-dependent dynamics like regular spikes ($T < 7.31$ °C), chaotic bursts (7.31 °C $\le T \le 10$ °C) and regular bursts ($T > 10$ °C) [35].

We employ scale-free network generated via growth and preferential attachment proposed by Barabási and Albert [36]. The present network comprising $N = 100$ neurons (nodes) starts with m_0 connected nodes, and subsequently every new node is attached to m ($\le m_0$) different nodes already present in the network, whereby the probability Π that a new node will be connected to node i depends on its degree k_i in accordance with $\Pi = k_i / \sum_j k_j$. The average degree of the network is $\langle k \rangle = \sum_i k_i / N$, and probability $P(k)$ that a node in the network interacts with k other nodes decays as a power-law following $P(k) \sim k^{-\gamma}$ with $\gamma = 2.9 \pm 0.1$ [36].

In the presence of electrical coupling, the dynamics of MHH neuron network with time delays is given by:

$$C\frac{dV_i}{dt} = -I_{iNa} - I_{iK} - I_{isd} - I_{isa} - I_{il} + \sum_j \varepsilon_{ij}\left(V_j(t-\tau) - V_i\right) + \xi_i(t), \tag{1}$$

where C is the membrane capacitance, V_i is the membrane potential of the ith neuron at time t; $I_{iNa} = \rho g_{Na} a_{Na} (V_i - V_{Na})$ and $I_{iK} = \rho g_K a_K (V_i - V_K)$ are the fast sodium and potassium currents, and $I_{isd} = \rho g_{sd} a_{sd} (V_i - V_{sd})$ and $I_{isa} = \rho g_{sa} a_{sa} (V_i - V_{sa})$ are the currents for "slow depolarization" and "slow after hyperpolarization". These currents relax according to $\frac{da_{Na}}{dt} = \frac{\phi}{\tau_{Na}}\left(a_{Na,\infty} - a_{Na}\right)$, $\frac{da_K}{dt} = \frac{\phi}{\tau_K}\left(a_{K,\infty} - a_K\right)$, $\frac{da_{sd}}{dt} = \frac{\phi}{\tau_{sd}}\left(a_{sd,\infty} - a_{sd}\right)$, and $\frac{da_{sa}}{dt} = \frac{\phi}{\tau_{sa}}\left(-\eta I_{isd} - \chi a_{sa}\right)$, respectively. $\rho = 1.3^{(T-T_0)/10}$, $\phi = 3.0^{(T-T_0)/10}$. $a_{Na,\infty} = a_{K,\infty} = \frac{1}{1+\exp[-0.25(V_i+25)]}$, $a_{sd,\infty} = \frac{1}{1+\exp[-0.09(V_i+40)]}$, $T_0 = 25$ °C, $T = 8.2$ °C, $\eta = 0.012$ μA, $\chi = 0.17$. $I_{il} = g_l (V_i - V_l)$ is leakage current. $\xi_i(t)$ is Gaussian white noise with zero mean and autocorrelation $\left\langle \xi_i(t)\xi_j(t') \right\rangle = \lambda \delta_{ij} \delta(t - t')$, noise intensity λ is fixed $\lambda = 0.02$. $\sum_j \varepsilon_{ij}\left(V_j(t-\tau) - V_i\right)$ is electrical coupling term, $V_j(t-\tau)$ is the membrane potential of the jth neuron at earlier time $t - \tau$, and τ (in unit of ms) is the information transmission delay between neurons i and j.

If chemical coupling is applied, the coupling term can be replaced by $\sum_j \varepsilon_{ij} r_j (t-\tau)\left[V_{syn} - V_i\right]$, thus we have

$$C\frac{dV_i}{dt} = -I_{iNa} - I_{iK} - I_{isd} - I_{isa} - I_{il} + \sum_j \varepsilon_{ij} r_j (t-\tau)\left[V_{syn} - V_i\right] + \xi_i(t), \tag{2}$$

and the synaptic dynamics of the jth neuron is described by a receptor binding as [37]:

$$\frac{dr_j}{dt} = \left(\frac{1}{\tau_{rise}} - \frac{1}{\tau_{decay}}\right)\frac{1}{1+\exp\left(-V_j - 20\right)}\left(1 - r_j\right) - \frac{1}{\tau_{decay}} r_j, \tag{3}$$

where V_{syn} is synaptic reverse potential, $r_j(t-\tau)$ is the fraction of bond receptors of the jth neuron at earlier time $t - \tau$. V_j is the membrane potential of the presynaptic neuron. τ_{rise} is the rise time constant, τ_{decay} is the decay time constant of synapse. The summation is taken over all neurons. Other parameter values are listed in Table 1. More interpretations of all parameters can be found in Refs. [34,35].

In coupling terms, ε_{ij} is coupling strength, which is assumed to be identical for any two neurons. If neurons i and j are connected, $\varepsilon_{ij} = \varepsilon$; otherwise, $\varepsilon = 0$. To simulate the fluctuations of coupling strength, we regulate ε by noise as:

$$\varepsilon = \varepsilon_0 [1 + \zeta(t)], \tag{4}$$