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Vibrational resonance in adaptive small-world neuronal networks with spike-timing-dependent plasticity

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HIGHLIGHTS

- Vibrational resonance in small-world neuronal networks with STDP is investigated.
- STDP can always improve the efficiency of network vibrational resonance.
- Small-world structure influences vibrational resonance of neural networks.
- Inhibitory synapses may weaken the effect of VR in the hybrid neuronal networks.

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ABSTRACT

The phenomenon of vibrational resonance is investigated in adaptive Newman–Watts small-world neuronal networks, where the strength of synaptic connections between neurons is modulated based on spike-timing-dependent plasticity. Numerical results demonstrate that there exists appropriate amplitude of high-frequency driving which is able to optimize the neural ensemble response to the weak low-frequency periodic signal. The effect of networked vibrational resonance can be significantly affected by spike-timing-dependent plasticity. It is shown that spike-timing-dependent plasticity with dominant depression can always improve the efficiency of vibrational resonance, and a small adjusting rate can promote the transmission of weak external signal in small-world neuronal networks. In addition, the network topology plays an important role in the vibrational resonance in spike-timing-dependent plasticity-induced neural systems, where the system response to the subthreshold signal is maximized by an optimal network structure. Furthermore, it is demonstrated that the introduction of inhibitory synapses can considerably weaken the phenomenon of vibrational resonance in the hybrid small-world neuronal networks with spike-timing-dependent plasticity.

1. Introduction

The dynamics of nonlinear systems are dramatically affected by the external influences, such as random noise [1–6]. One relevant presentative of this fact is stochastic resonance (SR) [7–11], where the response of a nonlinear system to a weak deterministic signal is enhanced by external random fluctuations. This phenomenon has attracted considerable interest recently, especially in excitable neuronal systems [12–15]. Moreover, it has been shown that the role of noise in nonlinear systems can be replaced by a high-frequency periodic force, which is well known as vibrational resonance (VR). The phenomenon of vibrational resonance occurs when a nonlinear system is subjected to two different periodic signals and

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the response amplitude of the system at the weak low-frequency periodic signal can be enhanced by appropriate amplitude of the strong high-frequency signal [16,17]. Up to now, the influence of vibrational resonance has been investigated in many fields, such as bistable laser systems [18], excitable electronic circuits [19], and periodic potential systems [20]. Numerical investigation suggests that it is the transition between different phase-locking modes that induces vibrational resonance in the excitable systems [21]. It is also indicated that the time delay plays a constructive role in the transmission of a low-frequency signal by inducing and enhancing VR [22–24].

As these two different frequency signals are ubiquity in brain dynamics—bursting neurons may exhibit two widely different time scales, the last decade has been growing body of modeling work on vibrational resonance in neural systems. For example, the occurrence of vibrational resonance was verified by Ullner et al. in the FitzHugh–Nagumo (FHN) neuron model [19]. It is shown experimentally and numerically that vibrational resonance affect is much more pronounced when the two frequencies are multiple [25]. Up to now, a series of studies have been focused on the vibrational resonance in complex neuronal networks, particular in small-world neuronal networks and scale-free neuronal networks [26]. The investigation of vibrational resonance in small-world neuronal network demonstrates that the effects of VR depend largely on the network structure and parameters such as the rewiring probability [27]. In addition, the effects of synaptic coupling on VR have been widely explored in the neuronal networks. It is indicated that chemical synaptic coupling is more efficient than the electrical one for the transmission of local input signal due to its selective coupling [28]. The study on vibration resonance in feedforward neuronal network (FFN) confirms that unreliable synaptic coupling can enhance the signal propagation in FFN [29].

However, most of the previous studies of vibrational resonance on complex neuronal networks were devoted to a static description of synaptic connectivity, while in reality the synaptic strength varies as a function of neuromodulation and timing-dependent processes. Spike-timing-dependent plasticity (STDP) is one of these important biological synaptic processes, which modulates the coupling strength adaptively based on the relative timing between pre- and post-synaptic action potentials [30,31]. Evidences in biological works have been accumulating to demonstrate the existence of STDP, which commonly occurs at excitatory synapses onto neocortical [32,33] and hippocampal pyramidal neurons [31,34], excitatory neurons in auditory brainstem [35], parvalbumin-expressing fast-spiking striatal interneurons [36], etc. Experimental researches show that the functional structures in the brain can be remapped through STDP, which is prevalently reorganized into both small-world and scale-free networks [37,38].

More recently, a series of modeling studies have been focused on the functional role of STDP in neural dynamics [39–43]. For example, Lee et al. use a simplified biophysical model of a cortical network with STDP, which provides a mechanism for potentiation and depression depending on input frequency, and suggest that the slow NMDAR current decay helps to regulate the optimal amplitude and duration of the plasticity [44]. In addition, it is shown that this plasticity of the coupling between neurons produces enlarged frequency-locking zones and results in synchronization that is more rapid and much robust against noise than classical synchronization arising from connections with constant strength [45]. Furthermore, it has been shown that STDP is crucial for shaping the network structure that achieves efficient processing of synchronous spikes and signal transmission [46–49].

In the present work, the pivotal effects of STDP on vibrational resonance in adaptive small-world neuronal networks will be studied. We aim to investigate how the network connections evolve during the process refined by STDP and the dependence of VR on it. Furthermore, fundamental roles of small-world structure and inhibitory synapses in networked vibrational resonance will be discussed. The remainder of this paper is organized as follows: in Section 2, a simplified model of hybrid small-world neuronal network is established and STDP rule is applied to modify the strengths of synaptic connections between neurons. Next, we explore the evolution of connection synapses via STDP within a high-frequency periodic driving background in Section 3. In Section 4, the dependence of vibrational resonance on STDP and small-world topology is systematically studied. We further examine the effect of inhibitory synapses on vibrational resonance in Section 5. Finally, a brief conclusion of this paper is drawn in Section 6.

2. Mathematical modeling

Based on Newman–Watts procedure [50], the neural network, consisting of $N = 100$ neurons, is initiated as a regular ring in which each unit is connected to its $K = 2$ nearest neighbors. Thus, the total number of shortcuts is $N(N-1)/2$. New shortcuts are added into the network with probability p, and the number of added shortcuts n_e satisfies $n_e = pN(N-1)/2$. If $p = 0$, the network is a regular ring, while it is globally coupled for $p = 1$. The small-world network is obtained by an intermediate case of p $(0 < p < 1)$. The normalized shortcut number p is one of the main parameters to be investigated in this paper. Initially, we shape the small-world neuronal network with purely excitatory synapses. Then we randomly change the synapses from excitatory to inhibitory with probability f. Hence, a hybrid small-world neuronal network with probability f of inhibitory synapses is obtained.

The FHN model is introduced to describe the neuron dynamics in the presence of two harmonic signals, which is governed by the following equations:

$$\varepsilon \frac{\mathrm{d}V_i}{\mathrm{d}t} = V_i - \frac{V_i^3}{3} - W_i + I_i^{syn} + A\sin(\omega t) + B\sin(\Omega t), \tag{1}$$

$$\frac{\mathrm{d}W_i}{\mathrm{d}t} = V_i + a - b_i W_i, \tag{2}$$