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The effects of time delay on the stochastic resonance in feed-forward-loop neuronal network motifs

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ABSTRACT

The dependence of stochastic resonance in the feed-forward-loop neuronal network motifs on the noise and time delay are studied in this paper. By computational modeling, Izhikevich neuron model with the chemical coupling is used to build the triple-neuron feed-forward-loop motifs with all possible motif types. Numerical results show that the correlation between the periodic subthreshold signal's frequency and the dynamical response of the network motifs is resonantly dependent on the intensity of additive spatiotemporal noise. Interestingly, the excitatory intermediate neuron could induce intermittent stochastic resonance, whereas the inhibitory one weakens its influence on the intermittent mode. More importantly, it is found that the increasing delays can induce the intermittent appearance of regions of stochastic resonance. Based on the effects of the time delay on the stochastic resonance, the reasons and conditions of such intermittent resonance phenomenon are analyzed.

1. Introduction

Noise is ubiquitous in both natural and engineered systems; its constructive role has been the subject of intensive studies for over a decade [1,2]. Especially, noise-induced complex dynamic behaviors such as stochastic resonance have been studied extensively in nonlinear dynamics [3–9]. Stochastic resonance is characterized by the optimal response of a nonlinear system to a weak external deterministic signal [10–14]. Notably, stochastic resonance has been extensively reported to exist in a wide variety of neuronal models [11,12,15,16]. Recently, Matjaž Perc et al. gave a detailed description of stochastic resonance on excitable small-world networks via a pacemaker. They showed that the correlation between the frequency of subthreshold pacemaker activity and the response of an excitable array is resonantly dependent on the intensity of additive spatiotemporal noise [17]. Additionally, further researches on stochastic resonance on weakly paced scale-free networks, diffusive networks and feed-forward neuronal networks of bistable oscillators show that an intermediate intensity of temporally and spatially uncorrelated noise can optimally assist the pacemaker in imposing its rhythm on the whole ensemble, thus, it provides evidence for stochastic resonance on weakly paced various types of the neuronal networks [18–20].

Recently, researches about the stochastic resonances on complex neuronal networks have attracted a great number of the attentions and the majority of previous researches deal with the dynamics of various complex neuronal system such as regular diffusively coupled networks [21,19], small-world networks [22] and scale-free networks [23,18,19]. Moreover, intensive statistical analysis has revealed that some significant recurring nontrivial patterns of interconnections, termed "network motifs," which are believed to be basic building blocks of various neuronal networks. Currently, network motifs are widely

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studied on neuroscience and suggested to perform specific functional roles [24,25]. A number of systematic research works have demonstrated that these motifs do exist widely in real biological networks, especially, in neuronal networks [26–28] and brain functional networks [29] by mathematical and experimental research. Previous studies have found that the motifs which are linked to each other in a special way remain their own independent function of each motif [30]. It suggests that the network dynamics might be understood as combinations of these elementary computational units [31]. And thus, the dynamics and special functions of these network motifs can be treated as the first step to understand the behaviors of whole networks.

The triple-neuron feed-forward-loop (FFL) is one of the most important neuronal network motifs [28]. In Ref. [28], three neurons are significantly over-represented relative to the expectations based on the statistics of smaller inter-connectivity patterns, as shown in Fig. 1, where neuron 1 drives neuron 2 and neuron 3, and neuron 2 drives neuron 3. In this motif, neurons 1, 2 and 3 can be regarded as the input, intermediate and output neurons, respectively. In consideration of the fact that neurons can be divided into excitatory and inhibitory neurons, eight possible structural configurations are obtained, as shown in Table 1, where E and I are used to represent excitatory and inhibitory neurons, respectively. Excitatory neurons encourage neurons to act the activity, whereas inhibitory ones play an opposite role. Recently, Li et al. have studied stochastic and coherence resonance in FFL neuronal network motifs [32]. They demonstrated the FFL motifs are more significant than the other simple chain structure as given in Ref. [33]. By comparison the effects of the stochastic resonance in the eight structural configurations, they showed that all possible structures can induce the optimal stochastic resonance in weak-coupling regime. However, the work in [32] did not consider the effects of time delay.

In real neural systems, time delays that mainly originate from the finite speed of action potential propagating across neuron axons and time lapses occurring by both dendritic and synaptic processes are inevitable in intermediate neuronal communication and inherent to the nervous system. Typical conduction velocities are approximately equal to 10 m/s, leading to non-negligible information transmission times, in the order of milliseconds or even hundreds of milliseconds [17]. It is found that time delay can not only facilitate and improve neuronal synchronization [34–37], but also induce multi resonances [38–42] leading to many interesting phenomena [43–45]. Moreover, it has been shown that time delays through chemical synapses play subtle roles in firing transitions, e.g., in-phase synchronization and anti-phase synchronization can be induced by time delays in map-based small-world neuronal networks with hybrid synapses [46].

At present, this paper aims to use computational modeling to systemically explore the dependence of stochastic resonance on the information transmission delay and the different structural configurations over FFL neuronal network motifs. Results show that the delay-induced stochastic resonance of the coupled neuronal network motifs can appear intermittently. Multiple stochastic resonances can occur on the neuronal network motifs if the durations of the delays are appropriately tuned. Accordingly, the remainder of this paper is organized as follows. In Section 2, the Izhikevich neuron model with chemical coupling is introduced. Section 3 is devoted to report the simulation results on the stochastic resonance in the FFL neuronal network motifs. Finally, a brief discussion and conclusion of our work are given in Section 4.

2. Model and method

Combine the biologically plausibility of Hodgkin–Huxley type dynamics and the computational efficiency of integrate-and-fire neurons, the Izhikevich neuron model is used to build the FFL neuronal network motifs [47]. The dynamics of the studied motifs is governed by the following two equations:

$$\frac{dv_i}{dt} = 0.04v_i + 5v_i + 140 - u_i + I_i^{noise} + I_i^{syn} + I_i^{ext} \tag{1}$$

$$\frac{du_i}{dt} = a(bv_i - u_i) \tag{2}$$

with the auxiliary after-spike resetting

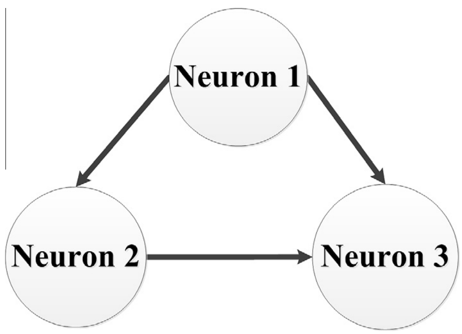

Fig. 1. Connection patterns of the FFL neuronal network motif: neuron 1 drives neuron 2, and both jointly drive neuron 3.