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Research paper

Stochastic resonance enhancement of small-world neural networks by hybrid synapses and time delay

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ABSTRACT

The synergistic effect of hybrid electrical-chemical synapses and information transmission delay on the stochastic response behavior in small-world neuronal networks is investigated. Numerical results show that, the stochastic response behavior can be regulated by moderate noise intensity to track the rhythm of subthreshold pacemaker, indicating the occurrence of stochastic resonance (SR) in the considered neural system. Inheriting the characteristics of two types of synapses—electrical and chemical ones, neural networks with hybrid electrical-chemical synapses are of great improvement in neuron communication. Particularly, chemical synapses are conducive to increase the network detectability by lowering the resonance noise intensity, while the information is better transmitted through the networks via electrical coupling. Moreover, time delay is able to enhance or destroy the periodic stochastic response behavior intermittently. In the time-delayed small-world neuronal networks, the introduction of electrical synapses can significantly improve the signal detection capability by widening the range of optimal noise intensity for the subthreshold signal, and the efficiency of SR is largely amplified in the case of pure chemical couplings. In addition, the stochastic response behavior is also profoundly influenced by the network topology. Increasing the rewiring probability in pure chemically coupled networks can always enhance the effect of SR, which is slightly influenced by information transmission delay. On the other hand, the capacity of information communication is robust to the network topology within the time-delayed neuronal systems including electrical couplings.

1. Introduction

The dynamical behavior of large-scale neuronal networks is closely related to brain functions [1–3]. Neural information processing in the brain is based on the coordinated interactions of large numbers of neurons within different brain areas. Although still a subject of research, the phenomenon of stochastic resonance (SR) provides new insights into the mechanisms of information processing in the brain [4–6]. Stochastic resonance is a process by which the ability of threshold-like systems to detect and transmit weak (periodic) signals can be enhanced by the presence of a certain level of noise [7–9]. Up to now, SR has been observed, quantified, and described in a series of realistic systems, especially in neural systems. It is shown that, SR in the central nervous system of mammalians may account for the higher brain functions, such as human tactile sensation, visual perception, and animal feeding behavior [10–12]. Thus, understanding potential benefits of SR in information processing of nervous systems is of great importance. On the other hand, the past decades have been growing

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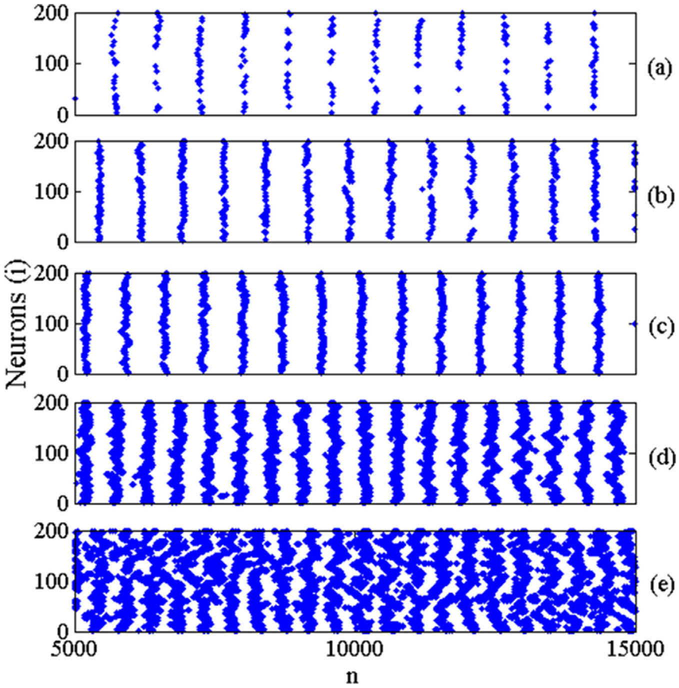

Fig. 1. Spatiotemporal patterns of the hybrid small-world neuronal networks obtained from different noise intensity σ with $f = 0.5$. (a) $\sigma = 0.015$, (b) $\sigma = 0.02$, (c) $\sigma = 0.026$, (d) $\sigma = 0.03$, (e)$\sigma = 0.04$.($\tau = 0$).

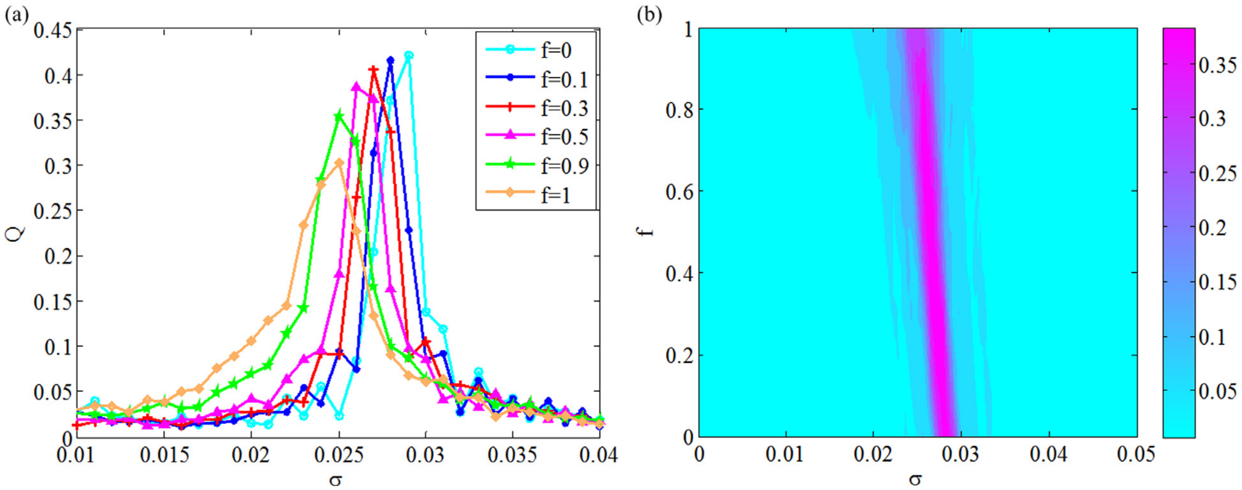

Fig. 2. (a) Dependence of Q on the noise intensity σ for different probability of chemical synapse. (b) Dependence of Q on the noise intensityσ and the chemical probability f.

body of modeling work on stochastic resonance in complex neuronal networks, which demonstrates that both the network property and coupling strength have a direct effect on SR in complex neuronal networks [13–18]. Particularly, Perc studied the SR in excitable small-world neuronal networks via a pacemaker, and found that the small-world property is able to enhance the stochastic resonance only for intermediate coupling strengths [19].

In neural systems, neurons contact with each other through two different types of synapses, electrical and chemical ones [20]. For electrical synapses, the coupling acts through gap junction, where the strength depends linearly on the difference between the membrane potentials [21,22]. That is to say, the electrical coupling can work as long as this potential difference exists. While in the chemical case, the synapse is mediated by neurotransmitters and the connection occurs between the dendrites and the axons. The chemical coupling emerges once the presynaptic neuron spikes and its strength decays exponentially afterwards [23,24]. Recently, since the evidences showed that electrical synapses and chemical ones can coexist in the neural system [25–30], the fundamental role of these two types of synapses on network dynamics has sparked increas-