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Firing patterns transition and desynchronization induced by time delay in neural networks

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HIGHLIGHTS

- We study the firing pattern transition (FTP) of Hindmarsh–Rose neural networks.
- We find that the FPT behavior can be induced by time delay in the neural network.
- We find that desynchronization behavior in the presence of time delay.
- We show that time delay can induce amplitude death in the neural network.
- We study the effect of coupling strength and network randomness on these phenomena.

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ABSTRACT

We used the Hindmarsh–Rose (HR) model (Hindmarsh and Rose, 1984) to study the effect of time delay on the transition of firing behaviors and desynchronization in neural networks. As time delay is increased, neural networks exhibit diversity of firing behaviors, including regular spiking or bursting and firing patterns transitions (FPTs). Meanwhile, the desynchronization of firing and unstable bursting with decreasing amplitude in neural system, are also increasingly enhanced with the increase of time delay. Furthermore, we also studied the effect of coupling strength and network randomness on these phenomena. Our results imply that time delays can induce transition and desynchronization of firing behaviors in neural networks. These findings provide new insight into the role of time delay in the firing activities of neural networks, and can help to better understand the firing phenomena in complex systems of neural networks. A possible mechanism in brain that can cause the increase of time delay is discussed.

1. Introduction

In recent decades, dynamic processes of coupled nonlinear systems or oscillators on complex networks have attracted much attention because such processes play important role in behaviors of various physical, chemical, and biological systems. The studied systems or problems include coupled nonlinear maps on a small-world network [1] and scale-free networks [2–4], synchronization of the stochastic Kuramoto model [5], coupled semiconductor lasers, coupled oscillation in

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chemically reacting cells, neutrino oscillations, infectious diseases, Josephson junction circuits [6–11], and biological neural networks [12–21]. In this paper, we will pay particular attention to biological neural networks, which play the key role in pattern recognition, associative memory, combinatorial optimization, and automatic control [22–25]. Neural networks encode, transfer, and integrate information by means of bursting behaviors [24].

Neural networks can exhibit rich and interesting dynamics. Periodic activities often occur in neural systems and can lead to serious diseases, such as Parkinson's disease, essential tremor, and epilepsy [26–28]. To terminate the seizure-like bursting behaviors, Wilson and Moehlis [28] proposed an effective method for driving a periodically bursting neuron to a sufficiently refractory target set. Multi-stability phenomenon can be observed in neural systems, e.g. in cortical neurons, the transition between spiking and bursting is corresponding to the transfer between sleep and wakefulness [29,30]. In neural systems, synchronous activity is of great significance in the information processing [31–33], people have performed intensive studies on the synchronization phenomena in neural systems and found rich phenomena [34–40]. Therefore, the study of the dynamics of neural networks plays a significant role in both understanding natural phenomena and designing useful procedures for solving practical problems.

Due to the external disturbance and finite speed of signal propagation and information processing, time delay naturally exists in neural networks. For instance, interactions between neurons are not always instantaneous, time delays can be up to 80 mini second (ms) for propagation through the coupled cortical networks [41]. Moreover, the effect of the sinoatrial node signal reaches the atrioventricular node after about 0.2 s in heart pacemakers [42]. As far as we know, time delay is a crucial factor affecting dynamic behaviors of many systems [43–45], such as synchronization, oscillations, chaos, multiple cycles and instability. Wang et al. found that time delays can facilitate neural synchronization and lead to many interesting and even unexpected pattern formation and synchronization, such as clustering anti-phase synchronization and in-phase synchronization [46–48]. Time delays can often induce interesting bursting behaviors, such as instabilities, bifurcations, multi-stability, and deterministic chaotic motions [24]. Time delay also plays significant role in the integration of information arriving to a single neuron in different temporal and spatial windows [8].

On the other hand, there has been an increasing interest and activities in the investigations on the dynamics of coupled systems with time delays. Proper time delay can be used to suppress instabilities, stabilize unstable or periodic states, and control complex chaotic phenomena. Particularly, time-delayed feedback strategy is an effective tool for controlling nonlinear dynamical systems. For example, in the coupled inter-system communication, the inherent oscillatory signal can be significantly controlled by time delays [49]. Buric et al. investigated the bifurcation relations among coupling time lag and coupling constant for different values of the internal time lags in a pair of FitzHugh–Nagumo systems with time delays [50]. Ge and Xu obtained the stability switches, synchronization, fold-Hopf, and double Hopf bifurcations in different bidirectional associative memory (BAM)neural networks consisting of coupled neurons in two layers and delayed couplings. They also clarified the relationships between complex dynamical behaviors and system parameters by a simple and effective perturbation incremental scheme [51–53]. Song and Xu [54] showed the rich coexistence of the different neural computational properties of a network consisting of two neural sub-networks with delayed couplings. Song et al. investigated the bifurcation, amplitude death, and oscillation patterns induced by the coupling time delay in a system of three coupled van der Pol oscillators [55]. To study cells, some researchers used this strategy to control complex networks, spatiotemporal patterns and noise-induced oscillations, bifurcation scenarios of optoelectronic oscillators, or genetic regulation and information processing [22]. All results mentioned above show that time delay plays an essential role in the response dynamics of neural systems.

Motivated by the above results, an intriguing problem is whether the time delay influences the periodic bursting behaviors in neural networks? And how the network controls the signal processing in real neural system? To this end, we considered a three-variable Hindmarsh–Rose (HR) model of membrane potential [12]. The HR model has been widely used to simulate spiking/bursting and chaos phenomena with the inter spike interval (ISI), we focus on the effect of time delay on the collective behaviors of neural systems. We construct a small-world network of N nodes, similar to that of [1], and each node is a HR neuron. In such a small-world network, there are local nearest neighbor couplings and a small number of shortcuts for non-neighboring nodes. The nerve impulse can transmit through the network by the presence of shortcuts. The coupling between two different neurons involves a time delay τ. With proper value of time delay τ, the coupled neuron system can show desynchronization, amplitude death and firing patterns transition (FPT) behaviors that include transition from the multi-period state to fewer-period one, and transition between periodic states and chaotic state. These results may be helpful for understanding the generation of membrane potential and the mechanism of information process in neural activities.

2. Model system

The HR model has long been studied as a mathematical representation of the firing behavior of neurons and has been used to represent neural systems in a wide variety of applications. It was originally introduced to give a qualitative explanation of the bursting type with long inter-spike intervals (ISI) of real neurons [12]. Using this neural model, the effects of time delay on firing dynamics have been widely studied [56–59]. The dynamics of an isolated HR neuron can be described by three-variable differential equations. Eq. (1) below can be used for a single neuron (cell) when $i = 1$ and $g = 0$. In reality, local coupling may correspond to the diffusion process between the nearest-neighbors, and the shortcuts to the electrical synaptic connections among non-neighboring neurons.