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Delay-induced synchronization transitions in modular scale-free neuronal networks with hybrid electrical and chemical synapses

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HIGHLIGHTS

- Time delay can induce synchronization transitions in modular neuronal networks.
- The transition is more profound for larger probability of electrical synapses.
- Modular network parameters can also induce transitions to burst synchronization.
- Two types of synapse can perform different but complementary synchronization roles.

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ABSTRACT

We study the dependence of synchronization transitions in modular networks of bursting neurons with hybrid electrical–chemical synapses on the information transmission delay and the probability of electrical synapses. The modular network is composed of subnetworks (clusters); each of them presents the scale-free property. It is shown that, irrespective of the probability of electrical synapses, the time delay can always induce synchronization transitions in modular neuronal networks. Regions of synchronization and non-synchronization appear intermittently as the delay increases. In particular, all these transitions to burst synchronization occur approximately at integer multiples of oscillatory period of individual neurons. In addition, for larger probability of electrical synapses, the intermittent synchronization transition is more profound, due to the stronger synchronization capability of electrical synapses compared with chemical ones. Furthermore, the transition to synchronous bursting can also be induced by the variation of modular network parameters, that is, the coupling strength between neurons, the interconnection probability between different subnetworks, as well as the number of subnetworks. Particularly, we find that a modular neuronal network is harder to get global synchronization when constituting neurons are dispersed over more clusters. On the other hand, chemical and electrical synapses can perform complementary roles in the synchronization of hybrid modular neuronal networks: the larger the electrical synapse strength is the smaller the chemical synapse strength needed to achieve burst synchronization.

1. Introduction

Synchronization in complex networks of coupled neurons has attracted great interest in recent years [1,2]. It is well-known that temporal coherence and spatial synchrony of neuronal spiking are very important for the efficient processing and

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transmission of information across the neural system [3,4]. In the last decades a great deal of theoretical and experimental works has been devoted to investigate the formation of synchronization in a vast variety of neuronal systems. In-phase and anti-phase synchronization have been studied in the networks of coupled map-based bursting neurons, and its generation mechanism was presented in Ref. [5]. Transition to burst synchronization has been studied in a diffusively coupled network of Hindmarsh–Rose neurons [6]. Moreover, dynamics of chaotic phase synchronization of bursting neurons has been investigated in many complex neuronal networks, which are locally modeled by a two-dimensional Rulkov map [7–9].

Latest developments in the quantitative analysis of complex neural networks, mostly revealed by anatomical, electroencephalographic (EEG), and neuroimaging data, demonstrate that the brain's structural and functional systems show some common features of complex networks [10–13]. For example, analysis of the connectivity between regions of the cerebral cortex in macaque monkeys and cats has revealed that the cortical neuronal networks are modular networks, i.e., composed of certain subnetworks with differential internal and external connectivity [14–17]. Modules of a complex network, also called communities or clusters, are subsets of nodes that are densely connected to other nodes in the same module but sparsely connected to nodes in other modules [18–20]. The organization of cortical areas into clusters permits the segregated processing of information of different modality [21]. More recently, synchronization in complex modular (or clustered) networks has been investigated [22–24]. For instance, Batista et al. have studied the synchronization dynamics of a clustered small-world network of bursting neurons and given bounds for the smallest coupling strength needed to achieve global synchronization on the bursting time scale [25]. Moreover, Gao et al. have further constructed complex networks formed from interdependent networks [26] and the robustness of such interacting networks subject to cascading failures has been analytically studied [27].

On the other hand, recent experimental evidences show that some structural and functional brain networks in humans show the scale-free property [28–30], i.e., the connection probabilities follow a statistical power-law dependence [31]. As a consequence, in scale-free networks a few nodes are connected with a large number of other ones, whereas most of the nodes are connected with a small number of network units. Recently, scale-free neural networks have received a great deal of research attention. Models of neural systems with scale-free coupling architecture display enhanced memory capacity, computational power, and synchronizability [8,32]. Batista et al. have studied the onset of chaotic phase synchronization in scale-free networks of bursting neurons, and investigated the control of bursting synchronization by using a time delayed feedback [33].

The coupling between neurons may occur via two different types of synapses, the electrical and chemical ones. In the former case, the coupling occurs through gap junctions and its strength depends linearly on the difference between the membrane potentials. In the chemical case, the synapse is mediated by neurotransmitters and the connection occurs between the dendrites and the axons. Therefore, chemical synapse allows long range connections, which can generate more complex network structures. Electrical and chemical synapses coexist within the same neuronal networks, and each kind of synapse is known to be able to foster synchrony among oscillating neurons [34]. In order to well understand the role each type of synaptic coupling plays in the synchronization process, various investigations have been carried out recently. For instance, Baptista et al. have studied the combined action of chemical and electrical synapses on the synchronous behavior in small networks of Hindmarsh–Rose neurons, and found that both synapses work in a constructive way to promote complete synchronization [35]. In addition, Kopell have demonstrated that chemical and electrical synapses perform different but complementary roles in the synchronization of interneuronal networks [36].

In real neural systems, information transmission delays are inevitable in intra and interneuronal communication, mainly because of the finite speed of action potential propagating across neuron axons, also due to time lapses occurring by both dendritic and synaptic processes. Delays arising from the propagation of action potential in neuronal systems can amount to several tens of milliseconds [37]. It is thus important to understand how such temporal delays influence the dynamics of coupled neuronal ensembles. Recently, important effects of time delay on qualitative and quantitative properties of neuronal dynamics have been exhibited, such as introducing or destroying stable oscillations [38], enhancing or suppressing synchronization between neurons [39–41], as well as generating spatiotemporal patterns [42,43] and inducing multiple stochastic resonances [44–46]. Particularly, delay-induced synchronization transitions in complex networks of bursting neurons have been extensively studied. In small-world networks, short or moderate conduction delays favor synchronization for both chemical and electrical coupling, while long conduction delays always evoke anti-phase synchronization and clustering [47]. Furthermore, studies on delay-induced synchronization transitions in scale-free neuronal networks show that regular or irregular propagating fronts appear intermittently as the delay increases [48]. Wang et al. also demonstrate that integer multiples of information transmission delay can introduce exactly the same type of intermittent synchronization transitions, both for spiking and bursting, and independent of the interaction network, small-world or scale-free types [49–51].

As is well known, synchronization of complex neural networks results from the interplay between the intrinsic properties of the individual neurons, the properties of the synaptic coupling, the finite information transmission delays, as well as the complex network structure. Each property may play an important role in shaping the emergent synchronous behaviors. However, the underlying mechanisms for the occurrence of synchronization and the effects of these factors on synchronization in neural systems are far from being fully understood.

In order to explore this, in this paper we will study delay-induced synchronization transitions on modular networks of bursting neurons with hybrid synapses. The modular network is composed of subnetworks, each of them presenting the so-called scale-free property. The local neuron dynamics is modeled by a two-dimensional Rulkov map, and all neurons