Cooperative effect of random and time-periodic coupling strength on synchronization transitions in one-way coupled neural system: mean field approach

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Received: 2 November 2016 / Revised: 26 March 2017 / Accepted: 10 April 2017 / Published online: 24 April 2017
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Abstract The cooperative effect of random coupling strength and time-periodic coupling strength on synchronization transitions in one-way coupled neural system has been investigated by mean field approach. Results show that cooperative coupling strength (CCS) plays an active role for the enhancement of synchronization transitions. There exist an optimal frequency of CCS which makes the system display the best CCS-induced synchronization transitions, a critical frequency of CCS which can not further affect the CCS-induced synchronization transitions, and a critical amplitude of CCS which can not occur the CCS-induced synchronization transitions. Meanwhile, noise intensity plays a negative role for the CCS-induced synchronization transitions. Furthermore, it is found that the novel CCS amplitude-induced synchronization transitions and CCS frequency-induced synchronization transitions are found.

Keywords Random and time-periodic coupling strength · Synchronization transitions · Mean field approach · One-way coupled neurons

Introduction

It is well known that synchronization is crucial to the information transmission among coupled neurons, it is correlated with many physiological mechanisms of

normal and pathological brain functions (Wang et al. 2015a, b, 2016; Banerjee et al. 2016; Mehta et al. 2002) as well as with several neurological diseases (Wang et al. 2016; Levy et al. 2000; Mormann et al. 2003; Wu et al. 2014), such as epilepsy and tremor in Parkinson's disease. In the past decade, synchronization phenomena in coupled neural system has been extensively studied and many synchronization phenomena have been found, such as noise-induced synchronization (Wu et al. 2014; Wang et al. 2015b; Zhou and Kurths 2003; Perc 2009), bursting synchronization (Ngouonkadi et al. 2016), time delay-induced synchronization (Zhang et al. 2014), the partial synchronization (Steuer et al. (2012), the phase synchronization (Yu et al. 2011; Ngouonkadi et al. 2015). For instance, Zhang et al. (2014) studied the synchronization of time-delayed chemically coupled burst-spiking neurons with correlated noises. Ngouonkadi et al. (2015) reported phase synchronization of bursting neural networks with electrical and delayed dynamic chemical couplings.

In recent years, a novel phenomenon of synchronization transitions has been observed in neural system (Yu et al. 2015; Wang et al. 2008, 2013, 2015a, b, c; Wu et al. 2014; Zhang et al. 2013; Hao et al. 2011; Sun et al. 2011), such as coupling strength induced synchronization transitions in bursting neuron network (Wang et al. 2015b; Hao et al. 2011), intra- and interneuronal coupling induced synchronization transitions in a neuronal network of subnetworks (Sun et al. 2011), time delay induced synchronization transitions in two coupled fast spiking neurons (Wang et al. 2008) and noise-induced synchronization transitions in neuronal networks (Wang et al. 2015b; Wu et al. 2014). These phenomena show that the synchronization transitions of neuronal networks may be intermittently enhanced or reduced with the variation of coupling strength, noise

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intensity or time delay, which is crucial to the information transmission in neural systems (Wu et al. 2014).

As is known, neural networks are formed by a great number of neurons coupled via synapses. Up to now, there are many studies presenting the effects of the coupling type and the strength on the firing behavior of the complex neuronal networks, and on the phenomena emerging in that networks (Wang et al. 2008, 2013, 2015a, b; Wu et al. 2014; Zheng et al. 2014; Zhang et al. 2013; Hao et al. 2011; Sun et al. 2011; Yilmaz et al. 2015). However, the aforementioned studies considered that coupling strength among coupled neurons is constant (Wang et al. 2008, 2013, 2015a, b; Wu et al. 2014; Zheng et al. 2014; Zhang et al. 2013; Hao et al. 2011; Sun et al. 2011). In fact, experimental studies have shown that synapses have a feature of plasticity, i.e., the ability of the connection between two neurons to change in strength in response to either use or disuse of transmission over synaptic pathways. Therefore, the coupling of neurons is random and time-varying, and neural networks are adaptive (Bîrzu and Krischer 2010; Xu et al. 2013; Wu et al. 2015). Bîrzu and Krischer (2010) have performed a modeling study on the effect of time-periodic coupling strength (TPCS) on the firing dynamics of a globally coupled array of Fitzhugh–Nagumo oscillators and have found rich oscillatory and resonant behaviors due to TPCS. Xu et al. (2013) studied the effect of time-periodic coupling strength (TPCS) on the synchronization of firing activity in delayed Newman–Watts networks of chaotic bursting neurons. Wu et al. (2015) studied the random coupling strength-induced synchronization transitions in neuronal network with delayed electrical and chemical coupling. Furthermore, it is well established that the unidirectionally coupled neural model is motivated by biological problems related to the dynamics of central pattern generators, which are responsible for the control of every rhythmic activity in animals (Li and Lang 2006; Stein et al. 1997).

Based on previous work in neural networks (Wang et al. 2008, 2013, 2015a, b; Wu et al. 2014; Zheng et al. 2014; Zhang et al. 2013; Hao et al. 2011; Sun et al. 2011) and the significance of a unidirectionally coupled neural model (Li and Lang 2006; Stein et al. 1997), our purpose is to study the cooperation effect of one-way coupled, random coupling strength (RCS) and time-periodic coupling strength (TPCS) on synchronization transitions in coupled neural system by mean-field approach. We expect that the present work will help us to reveal the importance of synchronization transitions in human brain, indeed, it is expected that the results in this paper might be important in signal transmission in human brain, and might be exploited in controlling neurological diseases.

The remainder of this paper is structured as follows: In section “**Dynamical model and methods**” we introduce the model and mathematical methods presently in use. Results and discussion are presented in third section, and in section “**Conclusions**” we summarize our results.

Dynamical model and methods

The Fitz Hugh–Nagumo (FHN) model is a simple but representative example of excitable systems (FitzHugh 1961). Its dynamic equations are expressed as follows:

$$\begin{aligned}\varepsilon \frac{dx}{dt} &= x - x^3/3 - y \\ \frac{dy}{dt} &= x + a\end{aligned}\quad (1)$$

where $\varepsilon = 0.01$, and a is the control parameter. For $|a| > 1$, the system has only a stable fixed point, while for $|a| < 1$, a limit cycle appears. To study the synchronization transitions phenomenon along the coupling chain, one-way coupled FHN system is introduced as follows:

$$\begin{aligned}\varepsilon \frac{dx_i}{dt} &= x_i - \frac{x_i^3}{3} - y_i + f(x_{i-1} - x_x) \\ \frac{dy_i}{dt} &= x_i + a_i\end{aligned}\quad (2)$$

Herein, i is running from 1 to 20. We set a_i ($i = 1, \dots, 20$) to be $a_0 = 1.05$, which is slightly larger than 1, such that all neurons in the coupled system are in steady state. Meanwhile, the random coupling strength (RCS) $f_1 = f_0 D \xi(t)$ and time-periodic coupling strength (TPCS) $f_2 = f_0 A \sin(wt)$ are employed to study the synchronization transitions, so the cooperative coupling strength (CCS) denotes as: $f = f_0 + f_1 + f_2$, i.e., $f = f_0(1 + D \xi(t) + A \sin(wt))$, where f_0 is the fixed coupling strength, D is the intensity of common Gaussian white noise $\xi(t)$ of cooperative coupling strength (CCS) with zero mean value $\langle \xi(t) \rangle = 0$ and unit variance $\langle \xi(t) \xi(t + \tau) \rangle = \delta(\tau)$, A and w are the amplitude and frequency of cooperative coupling strength (CCS), respectively (Yilmaz et al. 2015; Wu et al. 2013, 2015; Xu et al. 2012; Lin et al. 2011; Guo 2011).

To quantify how good the synchrony is, the order parameter O is calculated, which has been used to measure the synchronization of multicellular circadian oscillators (Gonze et al. 2005; Wu and Jia 2007):

$$O = \frac{\langle F^2 \rangle - \langle F \rangle^2}{\frac{1}{M} \sum_{i=1}^M (\langle x_i^2 \rangle - \langle x_i \rangle^2)} \quad (3)$$

$$F(t) = \frac{1}{M} \sum_{i=1}^M x_i(t) \quad (4)$$

where F is an average neurons level or a mean-field (Wu and Jia 2007), $\langle \cdot \rangle$ denotes the average over time. It is noted that O is ranging between 0 (no synchronous) and 1 (perfect synchronous, with all oscillators in phase) (Wu and Jia 2007). Equation (2) is integrated using the fourth Runge–Kutta method with a time step of 0.01 s. In each calculation, the time evolution of the system lasts 500 s, each data is obtained by averaging 20 runs.

Results and discussion

The difference between the synchronization transitions for random coupling strength (RCS) and cooperative coupling strength (CCS)

To study the difference between the RCS-induced synchronization transitions and CCS-induced synchronization transitions, we investigate the dependence of the order parameter (O) on constant coupling strength f_0 at fixed noise intensity D (i.e., RCS-induced synchronization transitions) and on constant coupling strength f_0 at fixed noise intensity D , amplitude A and frequency w (i.e., CCS-induced synchronization transitions), respectively. It is easy to observe from Fig. 1a–d that three interesting features are clearly revealed:

- (1) The order parameter (O) on f_0 is increased firstly, reaches a “peak”, and then is decreased, which implies that RCS induced-synchronization transitions and CCS induced-synchronization transitions could be both achieved.
- (2) The curve of RCS-induced synchronization transitions is similar as that of CCS-induced synchronization transitions, which quantitatively characterizes that the same synchronization transitions could be induced under RCS and CCS.
- (3) The CCS-induced synchronization transitions is stronger than RCS-induced synchronization transitions. The result suggests that CCS plays an active role for the enhancement of synchronization transitions. Furthermore, it is found from Fig. 1a–d that the maximum order parameter difference ($\Delta O_{\max}$) between CCS and RCS is increased with the increment of noise intensity (D), i.e., the $\Delta O_{\max}$ is 0.0051 at $D = 0.01$; 0.0121 at $D = 0.03$; 0.0152 at $D = 0.05$; 0.017 at $D = 0.07$, respectively. Intuitively, we speculate that D might be an important factor for influencing the CCS-induced synchronization transitions and RCS-induced synchronization transitions.

The noise effect of cooperative coupling strength on synchronization transitions

It is known that neurons are noisy elements, and noise arises from many different sources, such as the quasi-random release of neurotransmitters by synapses and random synaptic input from other neurons (external synaptic noise), and the random switching of the stochastic gates of ion channels (internal channel noise) (Ngounkadi et al. 2015). Therefore, in what follows, we are interested in investigating how noise intensity (D) affects the cooperative coupling strength (CCS)-induced synchronization transitions. In Fig. 2 we plot the dependence of the order parameter (O) on constant coupling strength f_0 at fixed A , w and various D (i.e., the effect of D on CCS-induced synchronization transitions). It is clearly observed that the CCS-induced synchronization transitions are decreased with increasing of D , which suggests that D plays a negative role for the synchronization transitions. In order to confirm the result, the dependence of the order parameter (O) on D is investigate as shown in Fig. 3. It is seen from it that O is monotonously decreased as D is increased.

One notes that the present result is different from those in previous studies, where noise was favorable for the inducement and improvement of synchronization transitions in neuronal system (Wang et al. 2015b; Wu et al. 2014). For example, Wu et al. (2014) reported that synaptic noise can induce strong synchronization transitions for chemical coupling. Wang et al. (2015b) stated that the synchronization transitions became most obvious when channel noise intensity was optimal. The reason might be that the neurons can fire spikes under the inspiration of noise, and the spikes might have different characters because the different neuronal system have different inherent dynamics. That is to say, CCS-induced synchronization transitions strongly depends on noise and the intrinsic dynamics of coupled neurons (Wang et al. 2015b).

Above result shows that noise might produce a twofold effect: from one side, it progressively deteriorate the quality of synchronization transitions; from the other side, it anticipate the synchronization transitions, insofar as it yield a synchronization transitions peak occurring at proper noise intensity (Brugioni et al. 2005). Now let us shed light on the mechanism in Fig. 2, of which noise could play a negative role for the synchronization transitions. Actually, there exists a competition between noise-induced oscillations propagation induced by coupling and noise-induced oscillations process induced by noise in coupled neural system. For too weak noise intensity, noise-induced oscillations propagation induced by coupling is stronger than noise-induced oscillations process induced by noise, which leads that the neurons are highly synchronized and the synchronization transitions are strong; For too strong noise

Fig. 1 The dependence of the order parameter O on constant coupling strength f_0 . **a** f ($D = 0.01$, $A = 0.2$, $w = 0.03$) and f_1 ($D = 0.01$); **b** f ($D = 0.03$, $A = 0.2$, $w = 0.03$) and f_1 ($D = 0.03$); **c** f ($D = 0.05$, $A = 0.2$, $w = 0.03$) and f_1 ($D = 0.05$); **d** f ($D = 0.07$,

$A = 0.2$, $w = 0.03$) and f_1 ($D = 0.07$). The result shows that the CCS-induced synchronization transitions is stronger than RCS-induced synchronization transitions, which suggests that CCS plays an active role for the enhancement of synchronization transitions

Fig. 2 The dependence of the order parameter O on constant coupling strength f_0 for different noise intensity (D) at $A = 0.2$ and $w = 0.03$. As D increases from 0.01 to 0.09, the CCS-induced synchronization transitions are decreased. It suggests that D plays a negative role for the CCS-induced synchronization transitions

Fig. 3 The dependence of the order parameter O on noise intensity (D) at $f_0 = 0.35$, $A = 0.2$ and $w = 0.03$. As D is varied, O is monotonously decreased. This result further suggests that D plays a negative role for the CCS-induced synchronization transitions

intensity, noise-induced oscillations propagation induced by coupling is weaker than noise-induced oscillations process induced by noise, the neurons are in low synchronization, noise can change the synchronization transitions easily, thus reduce the synchronization transitions (Zhou et al. 2001).

The frequency and amplitude effects of cooperative coupling strength on synchronization transitions

Studies have already shown that, synapses are plastic, that is, coupling strength among neurons can change with time (Yilmaz et al. 2015). Xu et al. (2013) studied the effect of time-periodic coupling strength (TPCS) on the synchronization of firing activity in delayed Newman–Watts networks of chaotic bursting neurons, and found that time delay can induce more synchronization transitions in presence of TPCS compared to fixed coupling strength.

Enlightened by this result, we are asking how the frequency (w) and amplitude (A) of time-periodic coupling strength (TPCS) affect the CCS-induced synchronization transitions. In Fig. 4a, b the dependence of the order parameter O on constant coupling strength f_0 at fixed D , w and various A (i.e., the effect of A on CCS-induced synchronization transitions) is investigated. It is displayed that the CCS-induced synchronization transitions is enhanced when A is increased from 0.1 to 1.5 (see Fig. 4a), and then disappears as A is further increased from 1.5 to 3.1 (see Fig. 4b). Based on the results that the CCS-induced synchronization transitions can occur in the case of $A < 1.5$ and cannot occur in the case of $A > 1.5$, it could be suggested that the critical amplitude (A_{cr}) for disappearance of CCS-induced synchronization transitions seem to be about 1.5.

To gain more insights into the result, the contour plot of the order parameter O for various w and f_0 is shown in Fig. 5. It is clearly shown that the synchronization transitions are enhanced as A is increased from 0.1 to 1.5, and then disappears as A is further increased from 1.5 to 3.1, which illustrates that the critical amplitude (A_{cr}) might be about 1.5. The result is in good agreement with that in Fig. 4a, b.

Above results show that a time-periodic coupling strength (TPCS) can play a more constructive and efficient role in enhancing the CCS-induced synchronization transitions of coupled neurons (Xie et al. 2016). The reason might be the fact that TPCS serves as an external driving signal (energy reservoir). When TPCS amplitude or TPCS frequency is appropriate, the neuronal system may employ the driving energy to enhance the CCS-induced synchronization transitions. However, when TPCS amplitude or TPCS frequency is too large, it dominates the firing

Fig. 4 The dependence of the order parameter O on constant coupling strength f_0 for different amplitudes (A) at $D = 0.03$ and $w = 0.05$. As A is increased from 0.1 to 1.5 (a), the CCS-induced synchronization transitions are enhanced, and then disappears as A is further increased from 2.3 to 3.1 (b). The result illustrates that the critical amplitude (A_{cr}) for the destruction of the CCS-induced synchronization transitions is about $A_{cr} \approx 1.5$

activity, leading to the destruction of CCS-induced synchronization transitions (Wang et al. 2012).

In Fig. 6 the dependence of the order parameter O on constant coupling strength f_0 at fixed D , A and various w (i.e., the effect of w on CCS-induced synchronization transitions) is investigated. From Fig. 6a, b, two interesting results are displayed: (1) The CCS-induced synchronization transitions rises with the increasing of w from 0.01 to 0.05, reach the strongest at $w = 0.05$, and then drops as w is further increased from 0.05 to 0.09 (see Fig. 6a). The result reflects that the optimal frequency (w_{opt}) for the best CCS-induced synchronization transitions should be 0.05. (2) When w is increased from 0.09 to 0.2, all curves almost overlap (see Fig. 6b). The result implies that the critical frequency (w_{cr}) which could not further affect the CCS-induced synchronization transitions might be about 0.09.

Fig. 5 Contour plot of the order parameter O as functions of A and f_0 at $D = 0.03$ and $w = 0.05$. It is seen that O islands are enhanced from 0.1 to 1.5, and then keep unchanged as A is further increased from 1.5 to 3.1, suggesting that the critical amplitude (A_{cr}) for the destruction of synchronization transitions is about $A_{cr} \approx 1.5$. The result is in good agreement with that in Fig. 4a, b

To further have a global view for the CCS-induced synchronization transitions, the contour plot of O for various w and f_0 is drawn in Fig. 7a, b. It is found from Fig. 7a that the synchronization transitions is enhanced firstly and then decreased when w is increased from 0.01 to 0.09. From Fig. 7b, the synchronization transitions hardly change as w is further increased from 0.09 to 0.5. The result is in good agreement with that in Fig. 6a, b.

The tendency mentioned above indicates that at appropriate A and w , the energy of TPCS could be transferred and the response of the coupled neurons to the inherited information can be most effectively amplified. However, when A and w is too large, it seems that the cooperative effect between the constant coupling strength f_0 and A (or w) is robust and cannot be further influenced by A (or w), indicating that the information transmission between reaches the saturation. It is important to study the role of A and w in the information processing and transduction in neural systems under noisy background (Li and Liu 2006).

Based on above results, we could come to conclusions that the cooperative coupling strength (CCS) plays an important role in the occurrence, improvement or suppression of synchronization transitions in coupled neural system. In studying synchronization transitions, different clues to enhance, reduce or destroy it, have been found, such as coupling strength induced synchronization transitions in bursting neuron network (Hao et al. 2011), intra- and interneuronal coupling induced synchronization transitions in a neuronal network of subnetworks (Sun et al. 2011), time delay induced synchronization transitions in two coupled fast spiking neurons (Wang et al. 2008) and noise-induced synchronization transitions in neuronal networks (Wang et al. 2015b; Wu et al. 2014). In our present

Fig. 6 The dependence of the order parameter O on constant coupling strength f_0 for different frequency (w) at $D = 0.03$ and $A = 0.2$. **a** $w = 0.01, 0.05$ and 0.09 ; **b** $w = 0.09, 0.1$ and 0.2 . As w increases from 0.01 to 0.09, the order parameter O peaks become largest around 0.05 (**a**), which reflects that the optimal frequency (w_{opt}) for the best CCS-induced synchronization transitions should be 0.05. As w further increases from 0.09 to 0.2, all curves almost overlap (**b**), which implies that the critical frequency (w_{cr}) which could not further affect the CCS-induced synchronization transitions might be about 0.09

work, a clue to regulate the synchronization transitions is the modulation of noise intensity, the amplitude and frequency of CCS in a certain range. Since synchronization is correlated with many physiological mechanisms of normal and pathological brain functions. We expect that noise intensity, the amplitude and frequency of CCS can desynchronize groups of model neurons (Popovych et al. 2006) and can engineer the synchronization of action potentials in cultured neurons (Rusin et al. 2011). We also expect that the phenomenon of synchronization transitions in this work could have an effect of regulation on the

Fig. 7 Contour plot of the order parameter O as functions of w and f_0 at $D = 0.03$ and $A = 0.2$. As w increases from 0.01 to 0.09, O islands become highest at around 0.05, which represents the strongest synchronization transitions (a). As w further increases from 0.09 to 0.5, O islands hardly change, implying the synchronization transitions keep unchanged (b). The result is in good agreement with that in Fig. 6a, b

normal and pathological functions in the brain (Wang et al. 2015b).

Conclusions

The cooperative effect of random coupling strength (RCS) and time-periodic coupling strength (TPCS) on synchronization transitions in one-way coupled neural system has been investigated by mean field approach. Results show that cooperative coupling strength (CCS) plays an active role for the enhancement of synchronization transitions. There exist an optimal frequency of CCS which makes the system display the best CCS induced-synchronization transitions, a critical frequency of CCS which can not further affect the CCS induced-synchronization transitions, and a critical amplitude of CCS which can not occur the CCS induced-synchronization transitions. Meanwhile, noise intensity plays a negative role for the CCS-induced

synchronization transitions. Furthermore, the novel CCS amplitude-induced synchronization transitions and CCS frequency-induced synchronization transitions are found. We expect that the results in this paper might be important in signal transmission in human brain, and might be exploited in controlling neurological diseases.

Acknowledgements The authors acknowledge the financial support of the Natural Science Foundation of Guangxi Province No: 2013GXNSFAA019019 and the Natural Science Foundation of Guangxi Province No: 2013GXNSFAA019041.

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