



Desynchronization effects of a current-driven noisy Hindmarsh–Rose neural network

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ABSTRACT

We investigate the effects of an external current in a disordered Hindmarsh–Rose neural network. The external bias appears in the Hindmarsh–Rose equations as either a noise term (identical or not for all elements), or a sinusoidal drive with a phase delay between the neural units. The Hindmarsh–Rose units inside the network are non-identical and they are coupled through electrical synapses, which allow a gap junction. Measuring synchronization through the Kuramoto order parameter, that is sensitive to the synchronization among the units rather than to the regularities of the trajectories, one finds that common noise induces synchronization, while the distributed noise, as well as the distributed sinusoidal drive, can desynchronize the network. The dynamics of the neural units shows that the bursting behavior is systematically and progressively replaced by a firing activity that becomes similar to the form of the external current. Deep modifications of the single firing dynamics and of the synchronization between the units, systematically occur for a critical value of the control parameters, either the coupling strength, the external drive amplitude, or the noise intensity. We emphasize the desynchronization effect of an external current, an effect that can be relevant for epileptic seizures provoked by network synchronization. The objective of this comparison between different perturbations for the same network is to seek for possible indications of the most effective mean to induce desynchronization.

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1. Introduction

Synchronization is interesting in many scientific fields [1–3] and in networks of chaotic units such as the Hindmarsh–Rose (HR) neural system [4] that exhibits a peculiar interplay between static disorder and coupling variables [5]. Neural network synchronization depends on the network coupling [4,6] and on the stochastic influence [7]. In fact, the signal transmitted within a neural network is inevitably subjected to random disturbances from the environment, which could possibly lead to probabilistic loss of information in the transmission process [7].

The behavior of a neuron or of a neural network in the presence of noise shows also stochastic coherence and chaos suppression [8–10]. Also, noise improves the detection and transmission of weak signals in certain biological nonlinear systems, inducing stochastic resonance phenomena [11–13] or enhances the synchronization of neurons within a network [14]. The external current directly influences the neuron dynamics, for the current term can

vary the dynamical firing of an isolated neuron [4,6]. Thus, modifying the applied current, one can intuitively expect several changes in the neural network synchronization, either synchronization depletion or, for special values of the external perturbation, synchronization enhancement. The latter effect has been observed, through some measures of the coherence of the interspike times, in a single unit [15], in two uncoupled neuronal units driven by a common noise [16], and in coupled arrays [16,17], also with time delay [18]. Perturbations of the neural units are also practically relevant. As the neurostimulation technique allows to treat some neural pathologies [19], an extra current such as an external neural stimulation could result in an epileptic treatment (see Refs. [20–22], to name but few examples), for epileptic seizure has a close relationship with neural synchronized activity. (We parenthetically note that brain diseases could be linked to the special case of intermittent synchronization given by chimera states [23,24], that are outside the purposes of the present work.) Thus, it has been conjectured a practical use of external added currents that cause desynchronization, and could possibly have an effect on epileptic seizures. In this context it is relevant to compare different methods to ascertain the most effective one.

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The main purpose of this analysis is to study the network synchronization process and the individual firing activity of a neuron within nonidentical HR neural network subject to two kinds of currents: Gaussian white noise realized through a common or distributed stochastic process which directly influence the applied current [4,25] and a sinusoidal drive current [26]. We employ the coupling scheme for the HR network coupled through nearest-neighbors where electrical synapses realize a linear bidirectional coupling between the neurons. Electrical synapses have some advantages in the neural synchronization process, for their rapidity. Also, the bidirectional character of this type of coupling allows for mutual interaction, and thus it favors an effective information transmission even below the action potential threshold [27]. However, there are two kinds of synapses: chemical and electrical, which are involved in the synchronization process of a biological nervous system. To include both types of synapses in the same network one can consider a varying architecture as the time-varying networks of Hindmarsh–Rose units recently studied [28]. In the present work, we aim to emphasize the role of the bidirectional coupling and of the external current; thus it has been considered a network with a stable topology that only deals with electrical synapses. Thus, the coupling only includes the potential action variable of each neural unit to highlight the current impact on the potential firing of the HR units within the network. Both noise and the sinusoidal drive currents may affect the firing pattern of a single neuron dynamics, but for our purposes it is important to monitor the overall network bursting dynamics characteristics of the neural units. To this extent, one can analyze the overall degree of synchronization of the network, and it might be appropriate to use a modification of the Kuramoto order parameter [29–31] that is, roughly speaking, proportional to the fraction of synchronized units. The use of this order parameter applied to neuronal activity follows, in some sense, the original proposal of Wiener, as pointed by Strogatz [32], and allows to measure the degree of synchronization even in chaotic or irregular dynamics. Thus, the Kuramoto order parameter allows to monitor how, and in which measure, the external drive induces desynchronization.

The paper is organized as follows, in Section 2 we present the network equations, the external drives and the synchronization condition through the Kuramoto order parameter. In Section 3, we investigate the network synchronization induced by a common noise. In Section 4 we analyse the desynchronization occurring in the neural network when the effective current acting on the neural units include either a distributed noise or a sinusoidal drive. Section 5 ends the paper with conclusions and perspectives.

2. The network under external applied current

We here establish the model equations and the synchronization definition. The purpose is to ascertain synchronization of the dynamical states of non-identical coupled HR neural models. The stochastic HR neural network equations and the synchronization condition allows to numerically investigate the neural dynamical behavior and the collective synchronization within a network of nonidentical units under random fluctuations or a sinusoidal drive.

2.1. Noise

Noise in a neural system is a general term that describes the random influence on the transmembrane voltage of a single neuron and, by extension, on the firing activity of the neuronal network. Noise can influence the transmission and integration of signals from other neurons as well as alter [33] or even enhance [14,34] the firing activity of an isolated neuron or a whole neuronal network. Here, noise refers to the random electrical fluctuations within neuronal networks. Usually, noise occurs below the

voltage-threshold that is needed for an action potential firing, but sometimes it can be present in the form of an action potential [35,36]. The noise influence in the network in this investigation is assumed to be a noisy external current. Following the effective transmembrane current definition [8] which results from many unlike applied currents [25], it can be modeled for each neuron of the network as

$$I_{eff}^N = I_0 + \epsilon_i(t), \quad (1)$$

where $\epsilon_i(t)$ is the stochastic a white noise process acting on the i^{th} neuron [14,37,38]. The random process can be defined such that either it is different from a neuron to another one (distributed noise) or it is identical for all the neurons (common noise).

The term $\epsilon(t)$ has the statistical features and properties of a Gaussian distribution (Gaussian white noise) with amplitude D :

$$\langle \epsilon_i(t) \rangle = 0, \quad (2)$$

$$\langle \epsilon_i(t) \epsilon_i(t') \rangle = 2D \delta_i(t - t'). \quad (3)$$

2.2. Sinusoidal drive current

The applied current can be defined as a time-dependent injected current to the neuron [26,39]; This current I_{eff}^d can be cast in the form:

$$I_{eff}^d = I_0 + I_d \sin(\omega t + \phi_i), \quad (4)$$

where I_0 is the primary current coming from the ionic fluxes across the cytoplasm and I_d is the amplitude of the alternating drive current. The drive pulsation is $\omega = 2\pi/T$, and T is the corresponding period. The phase, $\phi_i = i2\pi/N$, is the time delay at which the drive reaches the i^{th} neural unit. In other words, one expects that as the external signal propagates across the neural network, it does not bias all units with the same phase. Instead, time delays in the propagation of the signal in the axon [40] are here neglected.

2.3. Network equations

The fundamental entity on which the neuronal network is built is the HR nonlinear system [41,42]

$$\begin{cases} \dot{x} = y - x^3 + ax^2 - z + I_0 \\ \dot{y} = 1 - dx^2 - y \\ \dot{z} = r[s(x - x_1) - z]. \end{cases} \quad (5)$$

which is a very useful mathematical model to replicate the entirely natural cell dynamical behavior and, especially, the excitability derived from a sufficient stimulus and bursting activity. The latter dynamics occurs on two time scale subsystems, named the fast and slow subsystems [6,41,42]. There is a wide spectrum of meticulous theoretical investigations concerning the properties and the peculiarities of the HR neuron dynamical behavior (e.g. [6,8,42–44] for further information and parameters explanation). The main parameter governing the excitability mechanism, equivalently interpreted as either the applied current or the fluxes of ionic charges across the membrane cell, is the term I_0 in Eq. (5). One can model random effects or a drive on a neuron substituting I_0 with the applied current $I_{eff}^{N,d}$ given by Eqs. (1) and (4). Thus, Eq. (5) becomes

$$\begin{cases} \dot{x} = y - x^3 + ax^2 - z + I_{eff}^{N,d} \\ \dot{y} = 1 - dx^2 - y \\ \dot{z} = r[s(x - x_1) - z]. \end{cases} \quad (6)$$

During its functioning, the HR neuron can enter in a chaotic regime for several values of the parameters a, d, I, r, s in Eq. (6). In spite of the appearance of a chaotic behavior, many chaotic HR neurons are able to synchronize in a network if some physical and

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