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A network of networks model to study phase synchronization using structural connection matrix of human brain

F.A.S. Ferrari [a,*], R.L. Viana [b], A.S. Reis [b], K.C. Iarosz [c], I.L. Caldas [c], A.M. Batista [c,d]

[a] Universidade Federal dos Vales do Jequitinhonha e Mucuri, Instituto de Engenharia, Ciência e Tecnologia, Janaúba, MG, Brazil
[b] Universidade Federal do Paraná, Departamento de Física, Curitiba, PR, Brazil
[c] Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
[d] Universidade Estadual de Ponta Grossa, Departamento de Matemática e Estatística, Ponta Grossa, PR, Brazil

HIGHLIGHTS

- Here, chemical and electrical synapses are considered to describe a neural network.
- The network exhibits phase synchronization depending on the synaptic strength.
- Different functional structures are observed as synaptic strength is varied.
- The observed synchronization can be suppressed by appropriated feedback signals.
- The suppression of synchronization depends on feedback intensity and time delay.

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ABSTRACT

The cerebral cortex plays a key role in complex cortical functions. It can be divided into areas according to their function (motor, sensory and association areas). In this paper, the cerebral cortex is described as a network of networks (cortex network), we consider that each cortical area is composed of a network with small-world property (cortical network). The neurons are assumed to have bursting properties with the dynamics described by the Rulkov model. We study the phase synchronization of the cortex network and the cortical networks. In our simulations, we verify that synchronization in cortex network is not homogeneous. Besides, we focus on the suppression of neural phase synchronization. Synchronization can be related to undesired and pathological abnormal rhythms in the brain. For this reason, we consider the delayed feedback control to suppress the synchronization. We show that delayed feedback control is efficient to suppress synchronous behavior in our network model when an appropriate signal intensity and time delay are defined.

1. Introduction

The cerebral cortex plays a key role in complex cortical functions, such as language, thought, perception, and memory [1]. It can be separated into areas according to their specific functions, known as cortical areas. Every cortical area is associated with one main function, such as process visual, taste, hearing, olfaction, and touch inputs or deliver motor commands [1]. One possibility for the emergence of specialized areas is the economic wiring. This way, it is easier for the brain to process information if the neurons that perform similar roles are closer [2]. The cortical areas are connected among themselves

* Corresponding author.
E-mail address: fabiano.ferrari@ufvjm.edu.br (F.A.S. Ferrari).

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through a complex pattern of connectivity [3]. The brain integrates the information from different cortical areas (and other brain areas) to produce a more complete information [4]. The interplay between the cortical areas and the complex structural network of the cerebral cortex produce the typical dynamical properties observed in the brain [5].

Neural synchronization in the cortex area can be observed in many species, for instance in humans, monkeys and cats [6]. Experimental evidences show that neural interactions can be modulated by means of neural synchronization, as discussed by Buehlman and Deco [7], where they proposed that synchronization works to optimize the information transfer. Previous results of simulations in the cat cortex showed that the synchronization process depends on the topological structure [8]. In monkeys, it was observed synchronization at gamma-frequency (35 to 90 Hz) when the cortex received proper stimulus [9]. According to measurements in monkeys motor cortex, during a task, neural ensembles can be synchronized at specific frequency bands [10]. In humans, EEG measures have revealed that synchronization of neural activity can be associated with conscious and perception [11]. Synchronization in human cortex has also been observed at the visual cortex, parietal and motor cortex [12]. Parameter spaces for the synchronization in the human connectome was done in [13]. There are works that simulate neural networks with the connectome topology [14,15].

Synchronization can occur in neural ensembles and, in some cases, has been related to pathological rhythms and illnesses, as Parkinson's disease [16,17]. Individuals with Parkinson's disease can exhibit excessive synchronization in the *Globus Pallidus*, leading to movement impairments [18]. According to Silberstein et al. [19], synchronization between cortical areas can be correlated with parkinsonism. One possibility to treat Parkinson's disease is the suppression of synchronization [20].

In this work, we propose a network of networks model based on a real structural connection matrix of human brain to study the synchronization effects. The network describes structural properties of the human cerebral cortex, and the data was kindly provided by Lo et al. [21]. In this network, the cerebral cortex was separated into 78 cortical areas by means of the Automated Anatomical Labeling (AAL) [22]. Every cortical area is represented by one site, the links between sites are proportional to the number of fibers between cortical areas and they were determined through diffusion MRI tractography methods [23]. In our model, each site consists of a network composed of coupled neurons with small-world properties (cortical network). Small-world networks are characterized by a short path length distance between neurons and high local clustering [24,25]. Many neural ensembles have been demonstrated small-world properties, such as the worm *C. Elegans* [24], cortical connection matrices of cats and monkeys [25,26]. Evidences suggesting that structural human brain cortex has small-world properties were found through MRI measures [27,28]. In addition, small-world structures has also been found at cortical columns in the human brain [29].

As local dynamics of the neuron we consider the two-dimensional map proposed by Rulkov [30]. This phenomenological model exhibits many neural dynamical features, like regular spike, burst, and chaotic spikes. These features are generated through the interplay between a fast and a slow variable [31,32]. This model has the advantage of being easy to implement numerically and it has good agreement with experimental results about neural synchronization [33,34].

One of our main results is to show that for the same anatomical neural network, the human cortex can present a huge amount of different complex functional structures as synaptic strength is varied. Moreover, we also show that a delayed feedback signal is efficient to suppress synchronous behavior in our network model.

The structure of the paper is the following: In the Section 2, we introduce our model of neural network and the local dynamics. Each cortical area is defined as one network, the networks are coupled to each other creating a network of networks structure (cortex network). The local dynamics is characterized by bursting activity. In Section 3, we present how to define a geometric phase to study phase synchronization, and how the Kuramoto order parameter can be used to quantify synchronization. In Section 4, we show the effects of suppression of synchronization for the proposed network. In Section 5, we present our conclusions and final remarks.

2. Network of networks model

2.1. Cortex network

The human structural connection matrix used in this work was constructed and kindly provided by Lo et al. [21]. A series of procedures must be done to build the structural network. First, Diffusion Weighted Images [35] are generated from MR measures, after several processes like image registration, spatial normalization and customized template creation, then a 78×78 weighted adjacency matrix W_{ij} is created. The weight in the matrix is determined according to the number of fibers and the fractional anisotropy. The number of fibers was determined using the Fiber Assignment by Continuous Tracking Algorithm [36]. Further details can be found in [21].

For the cortex network we consider the weight W_{ij} as the number of fibers between the cortical areas i and j (Fig. 1). We redefine the weight values (Fig. 1): 0 (white dots), 1 (red dots), 2 (blue dots), and 3 (black dots), where they are distributed by frequency of the interconnected fibers. This selection is to build a connectivity matrix with a heterogeneity less than the real human structural connection matrix.

The degree strength s_i [37], that provides the links intensity for each cortical area in terms of the weight, is given by

$$s_i = \sum_{j=1}^{P} W_{ij}, \tag{1}$$