



Network and external perturbation induce burst synchronisation in cat cerebral cortex



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ABSTRACT

The brain of mammals are divided into different cortical areas that are anatomically connected forming larger networks which perform cognitive tasks. The cat cerebral cortex is composed of 65 areas organised into the visual, auditory, somatosensory-motor and frontolimbic cognitive regions. We have built a network of networks, in which networks are connected among themselves according to the connections observed in the cat cortical areas aiming to study how inputs drive the synchronous behaviour in this cat brain-like network. We show that without external perturbations it is possible to observe high level of bursting synchronisation between neurons within almost all areas, except for the auditory area. Bursting synchronisation appears between neurons in the auditory region when an external perturbation is applied in another cognitive area. This is a clear evidence that burst synchronisation and collective behaviour in the brain might be a process mediated by other brain areas under stimulation.

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1. Introduction

The nervous system of mammals is responsible for collecting and processing information, where the signals are sent by neurons [1]. The propagation of neural signals occurs through electrical and chemical synapses, as a result of the difference in electric potential between the exterior and the interior of a neuron [2]. Neurons connect to each other forming complex layered structures [3]. The different cortical layers have particular distributions of neuronal cell types, as well as connections with other cortical and sub-cortical regions [4]. The mammalian brain is composed of distinct areas, the cerebellar cortex, and non-cortical nuclei. The cortex presents fundamental divisions such as the hippocampus formation, the olfactory cortex, and associated areas [5].

In this work we consider the cat cerebral cortex. Scannell and collaborators [6,7] have relevant results related to the cortical system of the cat. They showed the connection organisation, and reported that there are 1139 corticocortical connections among 65 cortical areas. The cortical areas are organised into four connectional clusters, corresponding to visual, auditory, somatosensory-motor, and frontolimbic areas [8].

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Here, we focus on dynamical features such as bursting synchronisation and desynchronisation [9]. Bursting synchronisation is thought to play relevant roles in information binding in the mammalian brain [10]. However, bursting synchronisation may be associated with pathologies like seizures [11] or Parkinson's disease [12]. For this reason, studies about synchronisation are of great interest to neuroscience.

Our purpose in this work is to study the burst synchronisation and desynchronisation in a neural network model of the cat brain, using the matrix of corticocortical connections in the cat [7]. The matrix represents the densities of connections in 65 cortical areas as undirected weighted adjacency. We describe each cortical area as a small-world network [13–15]. Small-world networks have been proposed to be an efficient solution for achieving phase synchronisation of bursting neurons [16]. In addition they have been found to be linked to different levels of models of the brain.

Small-world networks have been intensively investigated in computational neuroscience [17]. The characterisation can be made on two basic levels: a microscopic, neuroanatomic level, and a macroscopic, functional level. Studies at the former level are limited to those few examples in which there is available data on the neuronal connectivity, as the worm *Caenorhabditis elegans*, which is considered one of the simplest and most primitive organisms that shares essential biological characteristics of the more complex species [18]. Hilgetag and collaborators verified that anatomical connectivity matrices from studies of cat and monkey cortices exhibit small-world properties [19]. The combination of short path length and high clustering makes the small-world topology an attractive model for the studies about the connectivity of the nervous system [20,21]. Moreover, there have been studies of large-scale anatomical connection patterns of the human cortex using cortical thickness measurements from magnetic resonance imaging [22]. The human brain anatomical network at this level has an average path length and a clustering coefficient with values presented by networks with small-world property. Stam and collaborators, in a study of functional brain networks, observed that there is a loss of small-world network characteristics in patients with Alzheimer's disease, in particular with an increase of the average path length with no significant changes in the clustering coefficient [23].

At the macroscopic level of description of neural networks, the use of non-invasive techniques as electroencephalography, functional magnetic resonance imaging and magnetoencephalography provides anatomical and functional connectivity patterns between different brain areas [24,25]. This information provides a way to study the brain cortex, considering the latter as being divided into anatomic and functional areas, linked by axonal fibres. Scannell and coworkers have investigated the anatomical connectivity matrix of the visual cortex for the macaque monkey and the cat [6,7]. In both cases the values of the average path length and clustering coefficient are in accordance with expected small-world properties [6,7].

There have been relevant studies about synchronisation on networks of networks and, more particularly, in terms of burst synchronisation. Burst synchronisation has also been investigated in scale-free neuronal networks. Wang and collaborators studied the dependence of synchronisation transitions of bursting oscillations with the information delay in scale-free neuronal networks with attractive and repulsive coupling [26]. In addition to burst synchronisation, it was demonstrated the possibility of taming desynchronised bursting activity with finite information transmission delays in the Macaque cortical network [27]. With regarding to network of sub-networks, Sun and collaborators showed that several factors, as the probability of connections between different sub-networks and the number of sub-networks, can induce burst synchronisation transitions [28]. Moreover, the type of inter-neuronal synapses can affect the synchronous behaviour. Inter-neuronal networks can present a high level of synchronisation by enhancing the strength of electrical synapses, or by means of a suitable tuning of inhibitory synaptic delay, or by means of both [29].

Each node in our brain model is described by the Rulkov model [30], a discrete time system with two dimensions. The low-dimensionality of this map allow us to study large neural networks of approximately 10,000 neurons. This model is capable of producing irregular bursts similar to bursts observed in individual neurons through neurobiological experiments. The Rulkov model allows numerical simulations that demands less computational efforts than the ones required to simulate, for example the Hindmarsh–Rose model. It has been used in studies about control of bursting synchronisation [31], phase synchronisation in clustered networks [16], and suppression of bursting synchronisation [32].

Our main goal is to show that burst synchronisation in the brain might be a process mediated by other brain areas under stimulation. We also show that external perturbations induce synchrony behaviour in cognitive areas of the cat cerebral cortex. Burst synchronisation appears between neurons in the auditory region when an external perturbation is applied in another cognitive area. We consider perturbations that activate neurons in accordance with experimental results in that pulses of blue light are capable to induce neuronal spikes [33,34].

This paper is organised as follows: in Section 2 we introduce the network of Rulkov neurons and the cat brain matrix. In Section 3, we study the phase synchronisation of the cognitive areas according to electrical and chemical synapses. In Section 4, we analyse the effect of an external perturbation on the synchronisation. In the last, we draw the conclusions.

2. Network of Rulkov neurons

There is a wide range of mathematical models used to describe neuronal activity [30,35–37]. In this work we consider the phenomenological model proposed by Rulkov

$$x_{n+1} = \frac{\alpha}{1 + x_n^2} + y_n, \quad (1)$$

$$y_{n+1} = y_n - \sigma(x_n - \rho), \quad (2)$$

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