Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/bbe

Original Research Article

Susceptibility of switching between in-phase and anti-phase patterns in the network of relaxation oscillators

Elżbieta Olejarczyk [a,*], Hubert Ostaszewski [a,1], Pierre Meyrand [b,c], Tiaza Bem [a]

[a] Nałęcz Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences, Warsaw, Poland
[b] Univ. Bordeaux, IMN, UMR 5293, Bordeaux, France
[c] CNRS, IMN, UMR 5293, Bordeaux, France

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form
7 March 2014
Accepted 3 April 2014
Available online 19 April 2014

Keywords:
Electrical coupling
Gap junction
Multistability
Anti-phase pattern
Central Pattern Generators
Relaxation oscillators

ABSTRACT

Neural networks composed of two or four cells with combined, electrical and inhibitory, synapses and realized for various network topologies were examined. The aim of this study was to determine a set of phases of oscillatory cycle in which different patterns of activity, characteristic for such networks, can be switched under an external stimulus. In particular, we studied susceptibility of switching between in-phase (IP) and anti-phase (AP) patterns (and vice versa). Our results demonstrate that windows of switching between patterns are similar for networks with electrical and mixed synapses and, in general, relatively independent of the network topology. The only effect of the network topology is an increase of the robustness of the AP pattern in networks of ring-like connectivity. The switching window width and thereby the robustness of the transitions between patterns decreases with the increase of the electrical coupling strength.

1. Introduction

Neurons can be coupled by two kinds of synapses, chemical and electrical. Electrical synapses have the form of narrow gap between the pre- and post-synaptic neurons known as a gap junction. They conduct nerve impulses faster than chemical ones, but unlike chemical synapses they do not have gain, i.e. the signal in the post-synaptic neuron is the same or smaller than that of the originating neuron.

Electrical synapses have been shown to be important in regulation of neuronal and glial cell activity in developing, adult and injured central nervous system CNS [1–5]. Such synapses are constructed by intercellular channels that allow

* *Corresponding author at:* Nałęcz Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences, Trojdena 4 St., 02-109 Warsaw, Poland.
E-mail address: eolejarczyk@ibib.waw.pl (E. Olejarczyk).

[1] Till November 2011.

http://dx.doi.org/10.1016/j.bbe.2014.04.001

for cell-to-cell electrical communication as well as sharing small molecules. In vertebrates these channels are formed by a large family of hemi-channels called connexins [6,7]. Homologous molecules have been also found in invertebrates, where the gap junction protein is called innexin [8,9]. In both invertebrates and vertebrates systems gap junctions undergoes regulation of their expression and conductance. Different mechanisms are involved in these processes, from neuromodulation to transcriptional regulation [10–13] including activity dependent mechanisms [14]. For example, in the adult system the strength of gap junction conductance can be modified by many agents such as nitric oxide via cGMP [15] or dopamine [16,17]. Interestingly, in developing nervous system the expression of connexins increases during the first postnatal weeks in the cortex and then decreases [18,19]. Moreover, in the spinal cord similar changes occur during late embryonic and late postnatal life [18,20,21].

The aim of this work was to investigate the effect of electrical coupling strength on susceptibility of switching between in-phase and anti-phase patterns in so-called Central Pattern Generators (CPG). The CPG are neural networks which produce rhythmic patterned activity mainly controlling motor task in invertebrate and vertebrate nervous system. Since the pioneering work in invertebrate preparation such as stomatogastric nervous system in the crustaceans, the heart beat system in leech, locomotor system in crayfish the concept of CPG [22,23] was extended in vertebrates from lamprey to mammalian spinal cord [24]. Such scheme of organization has been proposed to be a useful concept to study network involved in more cognitive task, for example networks coding for spatial locations [25]. The generation of rhythmic patterns is based on the interplay between synaptic and cellular mechanisms whereas the flexibility expressed by such CPGs to respond to the external changes is mainly under control of a large variety of modulatory systems [26].

In this paper we are interested by CPG networks that express multi-stability. This is another phenomenon that may be involved in flexibility of generated patterns that may be controlled by transient signals incoming to the network, for example of sensory origin. Multi-stability consists of existence of multiple alternative stable network states, each of which corresponds to a different activity pattern that can be generated by the network. Importantly, transitions between such stable states are possible without any change of network parameters and can be produced by transient external stimulus, applied to some of the network cells [27–30]. It is therefore interesting to determine conditions in which the switching between various activity patterns is possible in response to a given external input and for a given set of model parameters. The conditions of switching between multi-stable patterns as well as properties of switching stimuli have been described in 2, 4 and 6-cell networks connected by fast inhibition and electrical coupling [29]. However, recently it was shown that different spatiotemporal patterns can be expressed also in population of neurons coupled solely by gap junctions without any chemical synapses [34]. It is therefore interesting to ask whether the switching windows in the network with mixed synapses are similar to those in which only electrical synapses are present. This issue is addressed in this study.

We use the network model, in which cells are modeled as relaxation oscillators, commonly used to model pacemaker cells. Relaxation oscillators are also applicable as models of spiking cells with fast regenerative and slow recovery variable [31,32] as well as firing rate models of populations of excitatory cells with synaptic depression or cellular adaptation in developing networks [33]. An important role of gap junctional coupling in developing CPGs networks has been already suggested in our previous study [27,34]. Our results indicate that in the multistable network with electrical connections only and without inhibitory synapses, as during the development, switching between activity patterns are possible and occur according to similar rules as in the network with mixed synapses.

2. Methods

The series of simulations were performed to study the multistability of the CPG networks. The basic element of the CPG, a single neuron, has the (non-dimensionalised) dynamics defined by the following set of differential equations:

$$\tau_v \frac{dV_i}{dt} = -[V_i + W_i - \tanh(g^{\text{fast}} V_i) + I_i^{\text{syn}} + I_i^{\text{el}} + I_i^{\text{in}}(t)] \quad (1)$$

$$\tau_W(V_i) \frac{dW_i}{dt} = -[W_i - g^{\text{slow}} V_i] \quad (2)$$

where

$$I_i^{\text{syn}} = \sum_{j=1}^{j=N} g^{\text{syn}} \sigma\left(\frac{V_j - \theta^{\text{syn}}}{k^{\text{syn}}}\right) \cdot (V_j - E^{\text{syn}}); \quad \sigma(x) = \frac{1}{1+e^{-x}} \quad (3)$$

$$I_i^{\text{el}} = \sum_{j=1}^{j=N} g^{\text{el}} (V^j - V^i) \quad (4)$$

$$I_i^{\text{in}}(t) \; - \text{ externally injected input current} \quad (5)$$

$$\tau_W(V_i) = \tau_2 + (\tau_1 - \tau_2) \cdot \sigma\left(\frac{V_i}{k^{\text{tw}}}\right) \quad (6)$$

V_i – membrane potential; W_i – slow recovery current dependent on membrane potential; g^{fast} – membrane conductance of the fast voltage dependent current; g^{slow} – conductance of slow recovery variable; g^{el} and g^{syn} – electrical and synaptic conductances; respectively; τ_v – membrane time constant; τ_w – time constant of slow current dynamics; τ_1 and τ_2 – minimum and maximum time constants determining the duration of the active and silent phases of the oscillator; k^{tw} – quantifies the rate of voltage dependence; θ^{syn} – threshold of the synaptic activation; E^{syn} – synaptic reversal potential; k^{syn} – steepness of the synaptic activation.

For tractability in the current work following parameters are identical for all junctions and neurons respectively, with following values: $g^{\text{fast}} = 2$, $g^{\text{slow}} = 2$, $\tau_1 = 5$, $\tau_2 = 50$, $k^{\text{tw}} = 0.2$, $\tau_v = 0.16$, $E^{\text{syn}} = -4$, $\theta^{\text{syn}} = 0$, $k^{\text{syn}} = 0.02$.

The model has been implemented as a set of Matlab functions which compute the quantities defined by the