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Stochastic resonance in feedforward acupuncture networks

Ying-Mei Qin [a,b], Jiang Wang [a,*], Cong Men [a], Bin Deng [a], Xi-Le Wei [a], Hai-Tao Yu [a], Wai-Lok Chan [c]

[a] School of Electrical Engineering and Automation, Tianjin University, Tianjin, China
[b] Tianjin Key Laboratory of Information Sensing and Intelligent Control, Tianjin University of Technology and Education, Tianjin, China
[c] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Effects of noises and some other network properties on the weak signal propagation are studied systematically in feedforward acupuncture networks (FFN) based on FitzHugh–Nagumo neuron model. It is found that noises with medium intensity can enhance signal propagation and this effect can be further increased by the feedforward network structure. Resonant properties in the noisy network can also be altered by several network parameters, such as heterogeneity, synapse features, and feedback connections. These results may also provide a novel potential explanation for the propagation of acupuncture signal.

1. Introduction

The propagation and processing of signals in an excitable system of oscillators are key elements of information exchange in neural networks. Effects of noise on signal transmission in excitable systems are broadly studied, and varieties of phenomenon have been found [1]. The most important and interesting one is stochastic resonance (SR), where noise at a proper intensity can optimize the response of a nonlinear system to subthreshold periodic signals [2–4].

Recently, following initial advances in understanding effects of noise on individual dynamical systems, the scope shifted to spatially extended systems [5,6], where it has been discovered that the spatiality may help to additionally enhance the signal transmission in the system. An optimal configuration of network exists in networks with different topology structures [7,8]. Delay-induced multiple stochastic resonances have also been observed [9,10]. In addition to enhancement of periodic signals, aperiodic stochastic resonance (ASR) is also widely studied [4,11]. Experimental studies in recent decades have shown that some biological functions are also improved by SR [12,13].

Multilayer feedforward network (FFN), which is one of the most extensively studied network structures, can characterize the properties of neural code propagation [14]. Each layer in this network is related to a functional group of neurons, and information is transmitted from one group to the next. In this framework, both rate coding and temporal coding exist and are related to the synchronized states (synfire chain activity) and desynchronized states, respectively [14]. Precisely timed sequential firings of neurons which are associated with temporal coding in FFN network are observed in a number of neural systems [15,16]. Resonance phenomena including coherence resonance and vibrational resonance have been studied in feedforward network structure [17,18]. Effects of noises on propagation of weak signals and frequency selectivity in FFN networks have also been studied [19,20]. However, effects of the network features, such as heterogeneity, connections

* Corresponding author. Address: School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China. Tel.: +86 022 27402293.
E-mail address: jiangwang@tju.edu.cn (J. Wang).

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and topology, on stochastic resonance properties have not been investigated systematically. In most previous studies about stochastic resonance, neurons and synapses are homogeneous, violating real conditions. Heterogeneity, which is ubiquitous in real world, has been found to have nontrivial effects in promoting network coherence [21]. It has also been found that heterogeneity plays an important role in controlling synchronization and spiking regularity of coupled excitable systems [22]. Some other collective behaviors appear in the network due to heterogeneity [23].

Acupuncture is an essential part of traditional Chinese medicine (TCM) and it has been proved to be effective for treatment of diseases [24–26]. Manual acupuncture (MA) with different amplitudes and frequencies differentially modulate cerebral blood flow velocity, arterial blood pressure and heart rate in human subjects [27]. However, why different types of manual acupuncture have different effects is still unknown. We have investigated the encoding and decoding mechanisms of acupuncture manipulation based on the spatiotemporal firing patterns [28]. To further understand the transmission of acupuncture signal, we construct the feedforward network model for the acupuncture signal transmission path to reproduce some experimental findings [29]. Further prediction about the transmission mechanism can be made based on this feedforward acupuncture network. In this study, we focus on the signal propagation properties in this network to explore the underlying mechanism of acupuncture.

This paper is structured as follows. Firstly, we introduce the FFN network structure based on the FitzHugh–Nagumo (FHN) model. Then we focus on the propagation of weak signals through multi-layers with different noise intensities. Influences of network properties such as linking probability, synapse time constant, heterogeneity and feedback connection on stochastic resonance are studied systematically. Finally, we discuss the correlation between these results and the acupuncture.

2. Description of a feedforward network

Multi-layer feedforward networks are commonly applied to study the spatial–temporal coding problem in sensory organs, where Information of stimulus is transmitted from one group to another [16]. The thing need to be highlighted is that the layers mentioned in the paper do not limit to the anatomical layers of certain tissue, such as those in the cortex. The layer can be considered as a more general concept, which refers to many neuronal populations functionally linked by feedforward connections.

2.1. The FitzHugh–Nagumo (FHN) model

The FitzHugh–Nagumo (FHN) model has essential neuronal properties such as threshold and refractoriness. A neural feedforward network of FHN neurons is constructed as shown in Fig. 1. There are 200 neurons in each layers without couplings between them. Each neuron receives synaptic inputs from the neurons in the previous layer with probability P. The network model is described as follows:

$$\begin{aligned} &\varepsilon\frac{dx_{i,j}}{dt} = x_{i,j} - \frac{x_{i,j}^3}{3} - y_{i,j} + I_{i,j}^{syn}(t) \\ &\frac{dy_{i,j}}{dt} = x_{i,j} + a_{i,j} - by_{i,j} + \xi_{i,j}(t) + I_{ext} \\ &I_{i,j}^{syn}(t) = -\sum_{k=1}^{N_{syn}} g_{syn}\alpha(t - t_{i-1,k})(x_{i,j} - V_{syn}) \end{aligned} \tag{1}$$

Here the layer indices are $i = 1, 2, 3 \ldots N_L$, and the neuron indices in each layer are $j = 1, 2, 3 \ldots N$. $x_{i,j}$ and $y_{i,j}$ denote the membrane potential and recovery variable respectively in each neuron. $I_{i,j}^{syn}(t)$ is the total of synaptic current of neuron j in layer i. $\alpha(t) = (t/\tau)e^{-t/\tau}$ where τ denotes the synapse time constant, and $\tau = 0.2$ ms unless mentioning specifically. N_{syn} is the total

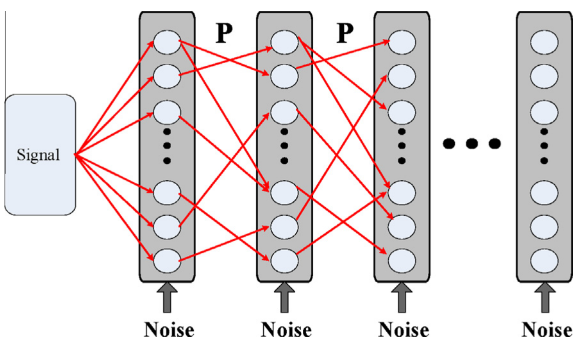

Fig. 1. A schematic of a multilayer feedforward network with 200 FHN neurons in each layer. P denotes the connection probability between the nearby layers.