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Dependence of Synchronization Coefficient Changing on Izhikevich Neuron Model After-Spike Reset Parameters for Ascending Information Flow in Cortical Column

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Abstract. The synchronization of neurons in cortical column for ascending information flow is considered. Graphics of the synchronization coefficient dependence on different variations of Izhikevich model parameters of after-spike reset were constructed. The raster plots were constructed for visual study of synchronization. Corresponding diagrams were plotted for the opportunity to compare the synchronization coefficient on different layers of cortical column.

Keywords: neuron dynamics; synchronization coefficient; cortical column; ascending information flow; raster plot; neuron modeling; Izhikevich model; after-spike reset parameters.

Problem statement. Researchers, who practice various specialties, such as biophysics, neurophysiology and medical informatics, are often interested in the issues of converting signals and information transmission in nervous system. Discovering the principles of representation and transformation of information in the human brain, depending on the architecture of its neural networks, are highly relevant research directions of modern science. Because of the complexity of setting real experiments, building computer models of neural networks plays very significant role in this process [1].

Analysis of recent researches and publications. One of the leading trends in modern neurobiology, neurophysiology and neuropsychology is a study of cognitive functions of human brain. One of the approaches of studying the processes occurring in such system is a use of dynamic models of neural networks of brain [2, 3]. The basic structural and functional unit of the cerebral cortex is a cortical column, i.e. vertically arranged rows of neurons linked predominantly with vertical connections [4, 5]. The shape of cortical column is still not fully defined, so each researcher chooses it at its own discretion - column, cylinder, cone, barrel or band, etc., the main thing is the vertical organization of internal connections. Cortical column passes through all layers of cortical cells.

Recent studies show that the implementation of many cognitive functions, such as the integration of features in a character, attention, perception, memory, are realized not only by modulating the level of neuronal activity, but also as a result of synchronization of neuronal activity between different brain structures [6].

The key role in the perception, selective attention and working memory is played by synchronous neuronal discharges which are recorded in various brain structures (thalamus, sensory systems, central olfactory cortex, neocortex). Synchronous neuronal activity supports the coordination of the locomotors system and provides life rhythms like breathing. On the other hand, the presence of synchronization is a sign of pathological abnormalities [7]. Disorders of the mechanism of generation of synchronous oscillations are one of the symptoms in patients with schizophrenia [8].

The purpose of article. The synchronization of neural network with the architecture of communications for ascending information flow is investigated. The neuron behavior is described by the Izhikevich model. The change of the synchronization coefficient, based on changes in neural activity, from model parameters of after-spike reset in cortical column is investigated.

Results and discussions. The human brain is a collection of cells (neurons) that communicate with impulses. The brain is based on a continuous process of formation and destruction of nerve connections. Nerve connections provide functional interaction between neural ensembles located in different parts of the brain. It is known that synchronous neural activity suggests the exchange of information between neurons and groups of neurons and it also suggests the establishment of functional connections between them. That is why the study of the structure of neural networks is one of the priorities of biophysics.

The homogeneous neural structure, i.e. a network in which all elements are identical and have the same neural connections, is investigated in this work. The studied neural system is fully connected, i.e. the system in which each element of the next layer takes synaptic current from all the neural elements of the previous layer and is connected to all neurons in its layer. The hierarchical structure of the network that was investigated in our work is shown in Fig. 1.

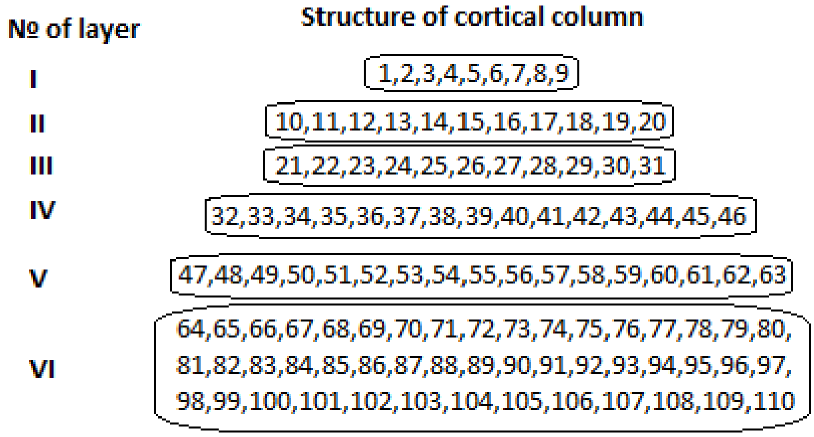

Fig. 1.The hierarchical structure of investigated network

To describe the neural element for such morphology network the mathematic neural model of Izhikevich was used. The neural model of Izhikevich is a two-compartment model that contains an additional requirement for cell membrane discharge:

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I, \quad \frac{du}{dt} = a(bv - u),$$

$$v \leftarrow c, u \leftarrow u + d, \text{ if } v >= 30 \text{ mV},$$

where v and u are the dimensionless membrane potential and membrane potential recovery variables respectively; *a, b, c and d* – dimensionless parameters. The variable u simulates the activation of ionic K^+ currents and the deactivation of ionic Na^+ currents and provides negative feedback to v. Variable I simulates external currents. Various choices of the parameters result in various intrinsic firing patterns, including those exhibited by the known types of neocortical and thalamic neurons [9].

The route of ascending information flow investigated in this work is displayed in Fig. 2. Information from the lower column always comes to the fourth layer - the main input layer. Then the cells of the fourth layer send projections up to the second and third layer inside the column, and then these layers are submitted to the input layer synapses of higher areas. In this way the information flows up to the hierarchy.

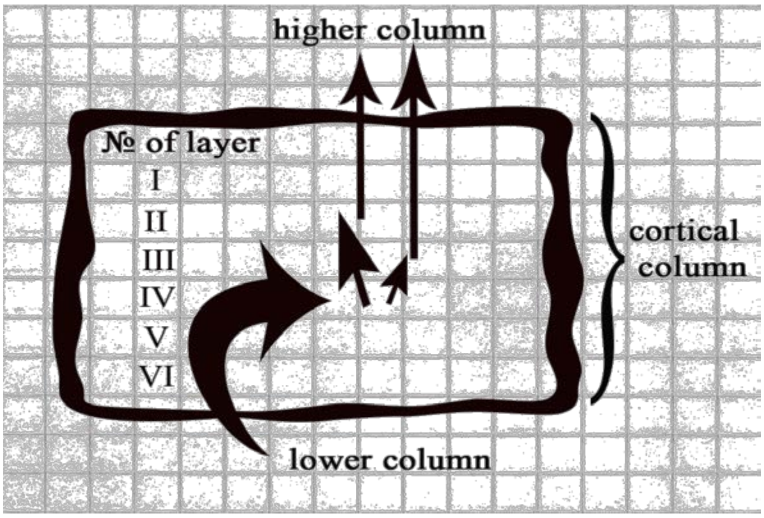

Fig. 2. The ascending information flow

From [10] the parameter *c* describes the after-spike reset value of the membrane potential *v* caused by the fast high-threshold K^+ conductance. A typical value is *c=-65 mV*. There was investigated the synchronization coefficient changes dependence on changes of parameter *c* for the whole cortical column (Fig. 3), and the diagram of layer dependence of synchronization coefficient on parameter *c* was constructed (Fig. 4).

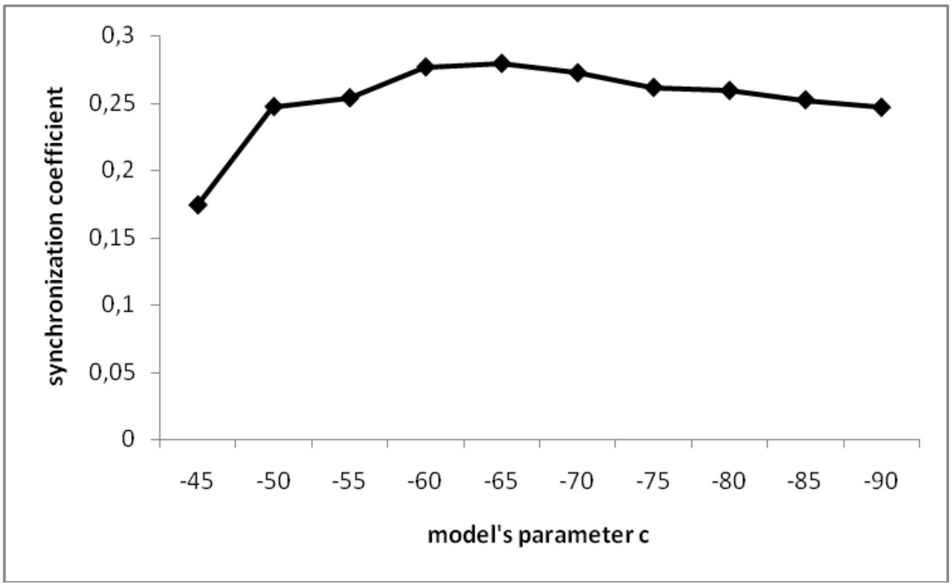

Fig. 3. Dependence of synchronization coefficient on parameter c

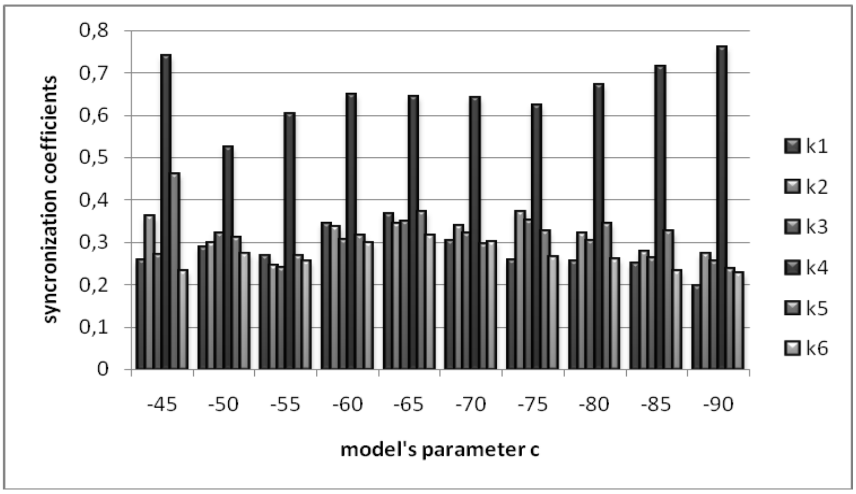

Fig. 4. Layer dependence of synchronization coefficient on parameter c

On the graphic of the synchronization coefficient dependence on parameter *c* we can see that values change fluently within *15%*. At *c=-65mV* the synchronization coefficient reaches the maximum - *k=0.279*. From Fig. 4 we can see the exceptionality of the fourth layer, on which the synchronization coefficient has higher value than on other layers, it changes in the limits of *k=[0.52; 0.76]*. On other layers the value of the synchronization coefficient is close to *0.3*. For *c=-65mV* the raster plot for ascending information flow in the cortical column was constructed (Fig. 5). Neural dynamics looks like *intrinsically bursting* (Fig. 6).

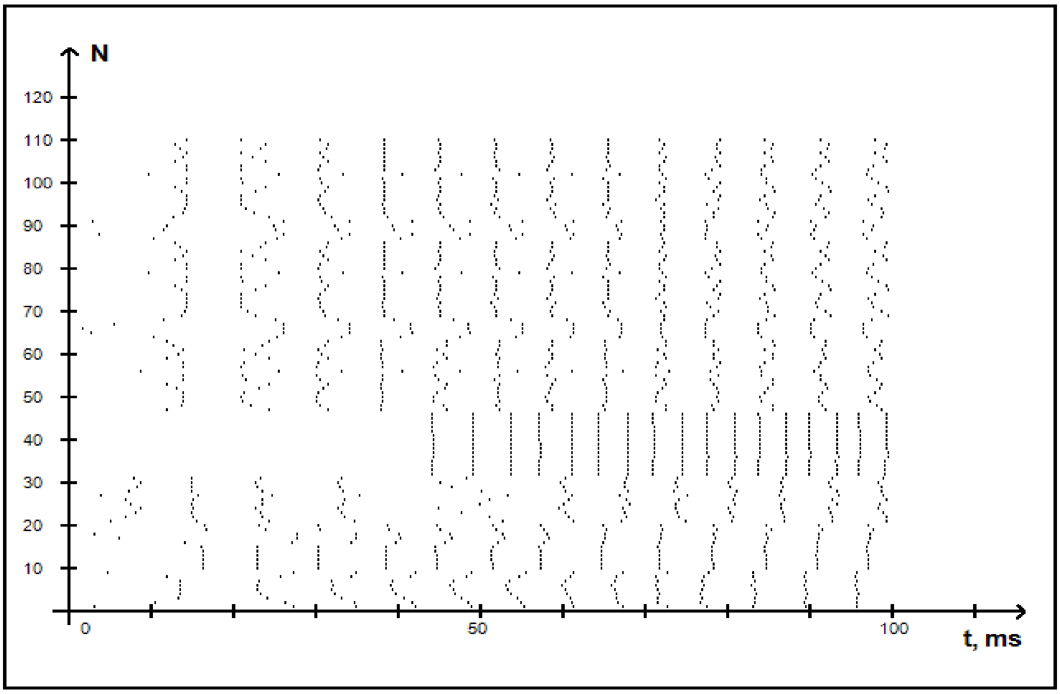

Fig. 5. The raster plot for c= -65 mV

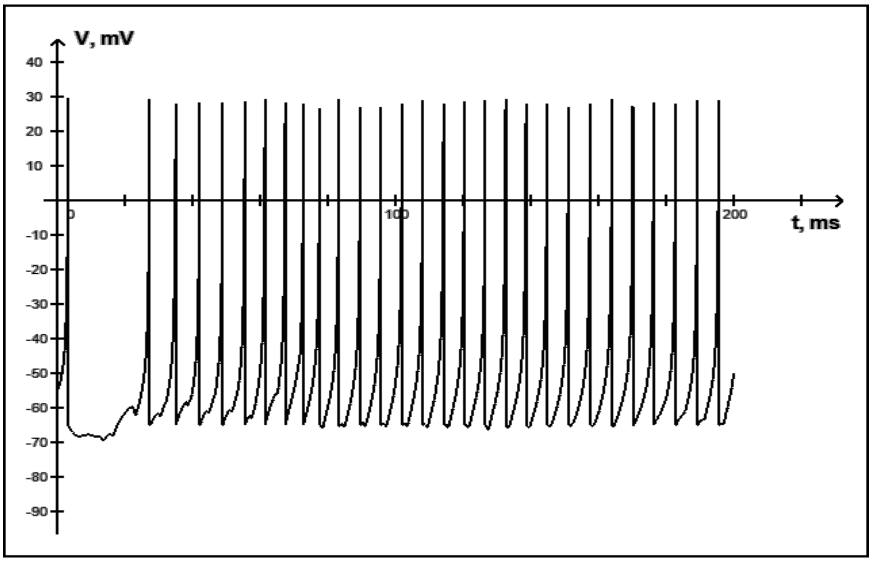

Fig. 6. Neural dynamics for c= -65 mV

From [10] the parameter *d* describes after-spike reset of the recovery variable *u* caused by slow high-threshold Na^+ and K^+ conductance. A typical value is *d =2*. There was investigated the synchronization coefficient changes dependence on changes of parameter *d* for the whole cortical column (Fig. 7), and the diagram of layer dependence of synchronization coefficient on parameter *d* was constructed (Fig. 8).

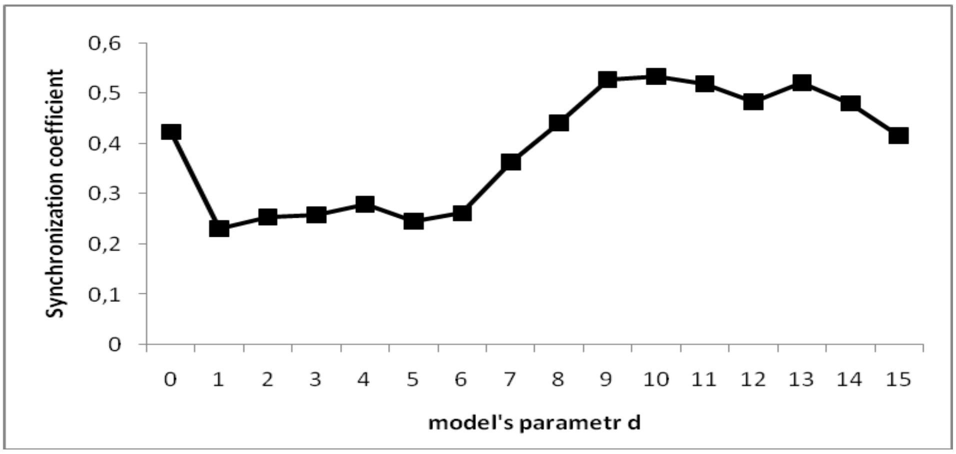

Fig. 7. Dependence of synchronization coefficient on parameter d

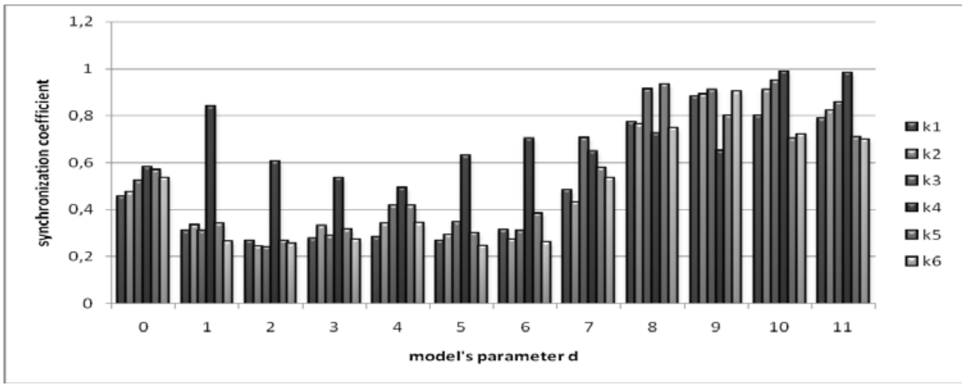

Fig. 8. Layer dependence of synchronization coefficient on parameter d

The graphic of the synchronization coefficient dependence on parameter *d* shows nonlinear dependence. During the previous parameters variations the synchronization coefficient does not exceed *30%,* but at parameter *d* the value of the synchronization coefficient reaches almost 60%. The minimum value of the synchronization coefficient *k=0.23* reaches at *d=1* and its maximum value *k=0.534* reaches at *d=10*. In the diagram (Fig. 8*)* we can also see an interesting situation which differs from previous one. The value of the synchronization coefficient arises with growth of parameter *d* on all layers, including the fourth input layer, on which at d=10 the synchronization is almost 100%. For *d=10* the raster plot for ascending information flow in the cortical column was constructed (Fig. 9). Neural dynamics looks like *regular spiking* (Fig. 10).

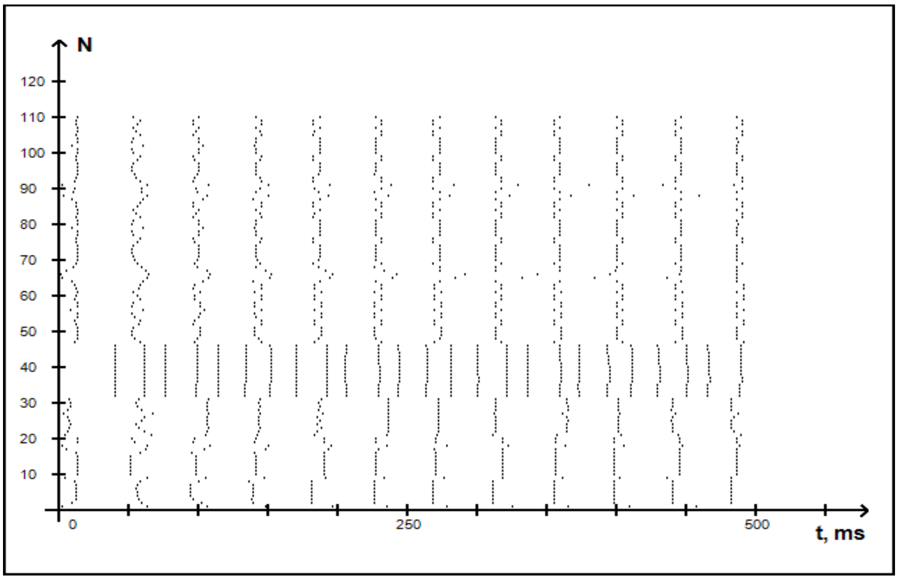

Fig. 9. The raster plot for d=10

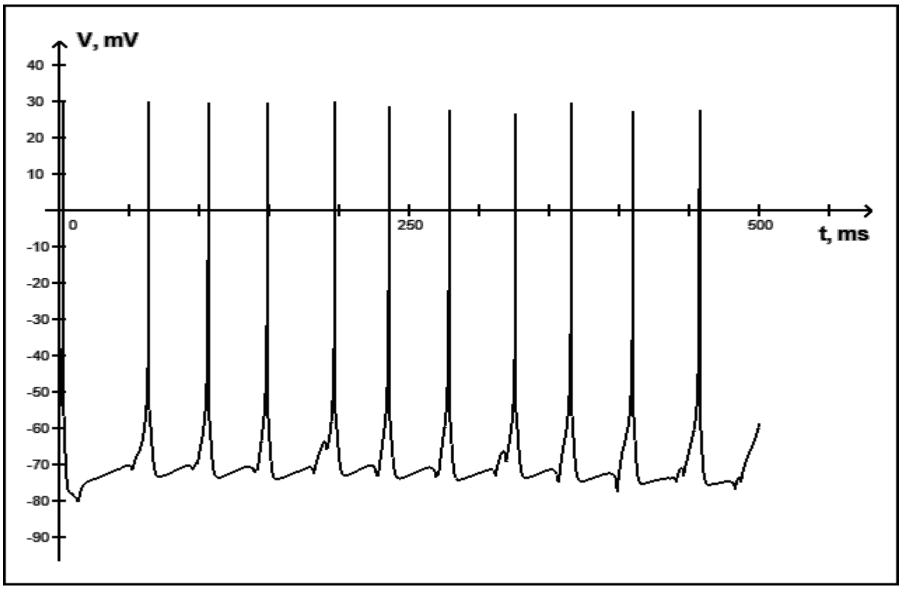

Fig. 10. Neural dynamics for d=10

Conclusions. Using experiment we can see that synchronous regimes arise during variations of Izhikevich model parameters. Researching of synchronization coefficient dependence on changing these parameters showed:

- neurons activity in the cortical column model is changed from the first to the sixth layer;
- the synchronization coefficient reaches its maximum at:

– at the parameter value $c = -65$ the synchronization coefficient $k = 0.279$;

– at the parameter value $d = 10$ the synchronization coefficient $k = 0.534$.

- the minimal synchronization coefficient is at the after-spike reset parameter c, and the maximum value of the synchronization coefficient is at the parameter d.

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Зависимость коэффициента синхронизации от параметров после спайкового сброса модели нейрона Ижикевича для восходящего информационного потока в кортикальной колонке.

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Аннотация. Рассмотрено синхронизацию нейронов для восходящего информационного потока в кортикальной колонке. Были построены графики зависимости коэффициента синхронизации в зависимости от вариаций параметров после спайкового сброса модели Ижикевича. Для визуального отображения картины синхронизации были построены растрограммы. Также были построены диаграммы для сравнения коэффициента синхронизации на разных слоях кортикальной колонки.

Ключевые слова: нейронная динамика; коэффициент синхронизации; кортикальная колонка; восходящий информационный поток; растрограмма; моделирование нейрона; модель Ижикевича; параметры после спайкового сброса.