Short-term memory in neuron-astrocyte network

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***Abstract*— In this paper, we study the role of astrocyte-induced modulation of signal transmission in network of synaptically coupled spiking neurons in the mechanisms of the short-term memory formation. We show, that due to the local spatial synchronization of signaling in the neural network induced by the astrocyte during the duration of the Ca^{2+} signal, the proposed neuron-astrocyte network can operate as a temporal Hopfield network.**

Keywords*— *Astrocyte, Short-term Memory, Neural Network

I. Introduction

Short-term memory modelling based on the neurobiology is an increasingly important tool to investigate the processes of learning, memory formation and the underlying neural plasticity [1]. Today modelling of memory functions grounded on the implementing of Hebb's theory [2] in biophysical neural network models is continuing to develop rapidly [1]. Recent models used in investigation the cortical short-term memory include an increasing diversity in terms of neuron types, physiology and architecture. However, there is a lack of studies dedicated to the role of the astrocytic modulation of synaptic transmission in mechanisms of the short-term memory. Recent experimental and theoretical studies [3-6] have shown that astrocyte can act as a temporal and spatial integrator, determining the level of spatiotemporal coherence in the activity of the accompanying neural network. In particular, such a spatiotemporal integration, based on fast and local events of activation of small compartments near astrocyte, leads to long-term astrocyte-mediated changes in the synaptic functionality of the neural network. Activation of astrocyte can induce spatial synchronization in neural ensembles defined by the morphological territory of astrocyte. In this paper, we continue to develop our previous short-term memory model [7] based on the effect of astrocyte modulation of synaptic transmission in neuron-astrocyte network.

II. Model and Architecture of a Neuron-Astrocyte Network

The neuron-astrocyte network consists of 2 layers: the first layer of neurons (dimension WxH (79x79)) and the second layer of astrocytes (dimension MxN (26x26)). Each astrocyte (m, n) interacts with N_a = 16 neurons (4x4 ensemble) with overlapping in one row Fig. 1.

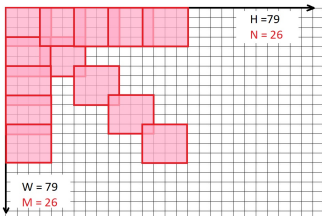

Fig. 1. The structure of the neuron-astrocyte network model.

A. Neural layer dynamics

The dynamics of the membrane potential of each neuron (i, j) is described by the Izhikevich model [8]:

$$\begin{cases} \frac{dV_{i,j}}{dt} = 0.04{V_{i,j}}^2 + 5V_{i,j} + 140 - U_{i,j} + I_{app_{i,j}} + I_{syn_{i,j}} \\ \frac{dU_{i,j}}{dt} = a\left(bV_{i,j} - U_{i,j}\right) \end{cases}$$

$$If\ V_{i,j} \geq 30\ mV, then\ V_{i,j} \rightarrow c,\ U_{i,j} \rightarrow U_{i,j} + d$$

where I_{app} – input signal, I_{syn} – synaptic current. The architecture of synaptic connections between neurons is random and fixed during one session. Each neuron linked to 40 others by exciatory synaptic connection. The postsynaptic neuron is sampled from radial exponential distribution centered in presynaptic neuron.

The synaptic current I_{syn} for each neuron (i, j) is determined by the equation:

$$I_{syn}(i,j) = \sum_{k=1}^{N_c^{i,j}} g_{syn}(k) \cdot S(k) \cdot \left(E_{syn} - V_{(i,j)}\right),$$

where:

$$g_{syn}(k) = \eta + \nu_{Ca},$$

$$S(k) = 1/(1 + exp\left(-\frac{V_{pre(k)}}{k_{syn}}\right)),$$

$$\nu_{Ca} = \begin{cases} 0.25,\ if\ Ca_{m,n} > 0.15\mu M, \\ 0,\ else \end{cases}$$

E_{syn} = 0, η = 0.025, k_{syn} = 0.2, N_c - number of input synaptic connections, ν_{Ca} - astrocyte effect on synaptic communication.

B. *Dynamics of astrocytes layer*

Dynamic of intracellular calcium concentration in each astrocyte (m, n) is described by the Li-Rinzel model [9]. State variables of each cell include IP_3 concentration – IP_3, Ca^{2+} concentration – Ca, and the fraction of activated IP_3 receptors – h. Astrocytes are interconnected due to diffusion of Ca^{2+} and IP_3. They evolve according to the following equations:

$$\begin{cases} \frac{dCa_{m,n}}{dt} = I_{channel} - I_{pump} + I_{leak} + I_{in} - I_{out} + dif_{Ca_{m,n}} \\ \frac{dh_{m,n}}{dt} = \frac{H - h_{m,n}}{\tau_n} \\ \frac{dIP_{3m,n}}{dt} = (IP_{3s} - IP_{3m,n})\tau_r + I_{plc} + I_{glu_{m,n}} + dif_{IP_{3m,n}} \end{cases}$$

Biophysical meaning of all parameters, variables and nonlinear functions described the biochemical transformation of Ca^{2+} dynamics in astrocyte can be found in [9].

C. *Neuron-astrocyte interaction*

Communicating between astrocyte and neurons based on two pathways. The first one involves glutamate neurotransmitter. In the case of the neuron spike occurring the concentration of neurotransmitters is increased by constant and then decreased exponentially with time. More than half of astrocytic connected neurons with high glutamate concentration for the previous 60 ms produce current I_{glu} in the astrocyte. This, in turn, initiates astrocyte calcium activity through IP_3.

The feedback of astrocytes modulates neuronal activity of postsynaptic neuron by increasing the strength of incoming synaptic connections [10]. This occur when there are both factors: the calcium event and spiking of at least half of astrocytic connected neurons in the last 5 ms. The calcium event is defined as exceeding of 0.15 μM calcium concentration.

III. Results

To understand the model capabilities we train our network to perform pattern recognition and noise dilution of input images. The network training process consists of presenting randomly black and white images (Fig. 2) with the addition of a random 5% noise ("salt and pepper noise"). Each image is presented 10 times for 0.5 ms with an interval of 4.5 ms. (see Fig. 3a – input signal, 3b – neural network response to the input signal). During training, each astrocyte tracks the activity of 16 neurons associated with it. After training, while the concentration of Ca^{2+} in the astrocyte exceeds the threshold of 0.15 μM (see Fig. 3c – the concentration of Ca^{2+} in astrocytes), feedback on the modulation of synaptic transmission by astrocytes is activated, which led to the increase in the synaptic strength between neurons. Thus, the neuron-astrocytic network remembers the training pattern for the period, which is determined by the duration of the Ca^{2+} pulse in the astrocyte. As a test, the image is presented with the addition of a random 20% noise ("salt and pepper noise") for 20 ms. Upon presentation of the test pattern (see Fig. 3d), the neural network identifies the target pattern (see Fig. 3e) by noise clearing due to astrocyte effects. The example of training and classifying a noisy image by a neuron-astrocyte network is shown in Fig. 3.

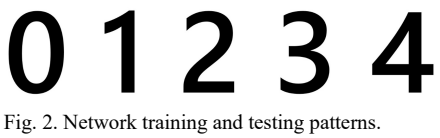

Fig. 2. Network training and testing patterns.

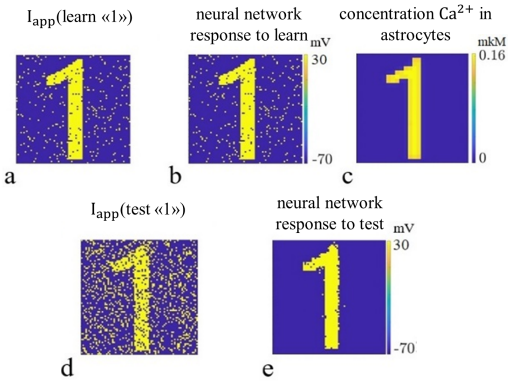

Fig. 3. Example of learning and recognition by the neuron-astrocyte network.

Figure 4a shows the membrane potential of one neuron located inside the "4" pattern, 4b shows the Ca^{2+} concentration in the astrocyte corresponding to this neuron.

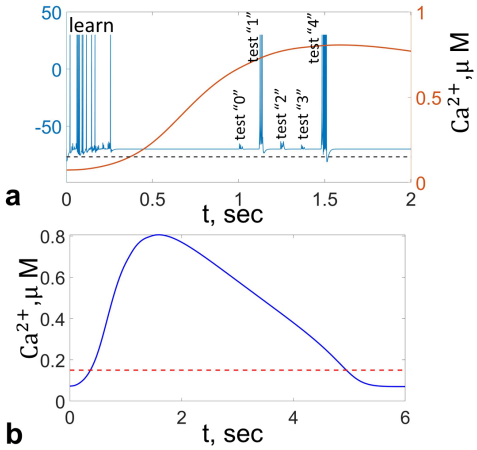

Fig. 4. a – membrane potential of neuron during training and test, a, b – concentration Ca^{2+} in astrocyte.

To test robustness to noise of the neuron-astrocyte network, we compute the pattern recognition accuracy (averaged over 5 patterns) for the different noise levels in the test (Fig. 5). To calculate the accuracy, we compared the response of the network with the ideal pattern (inside the image and background), normalized to the area, and averaged between them. The noise level in the learning stage is 5%.

The increasing of noise up to 30% is slowly degrade the accuracy to 0.9. At level 0.8 we manually set the reasonable threshold level.

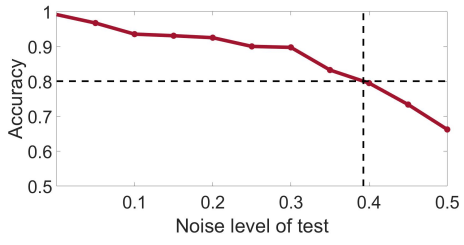

Fig. 5. The dependences of the accuracy on the noise level. Dashed line corresponds to manual selected threshold of accuracy.

IV. Conclusion

In this paper, we continue to study the role of astrocyte-induced modulation of signal transmission in network of synaptically coupled spiking neurons in the mechanisms of the short-term memory formation. We show, that due to the local spatial synchronization of signaling in the neural network induced by the astrocyte during the duration of the Ca^{2+} signal, the proposed neuron-astrocyte network can operate as a temporal Hopfield network.

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