A Biomimetic Neural-Astrocytic Network: Adding a Slow Layer for Fast Information Processing

Leo Kozachkov, Kevin T. Feigelis , Konstantinos P. Michmizos

Computational Brain Lab, Department of Computer Science, Rutgers University, NJ, USA

Figure 1

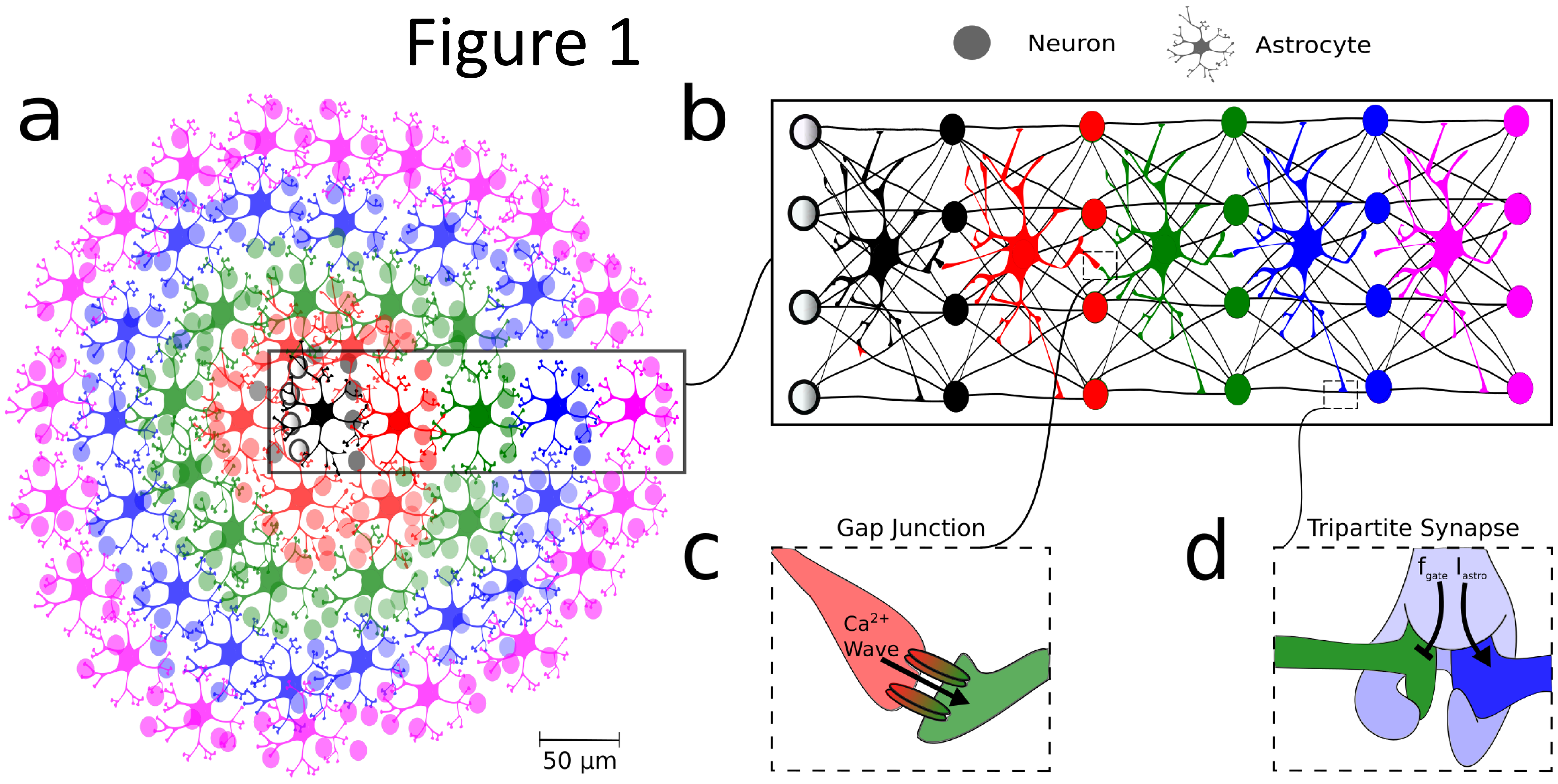

Figure 2

Network Firing Rate

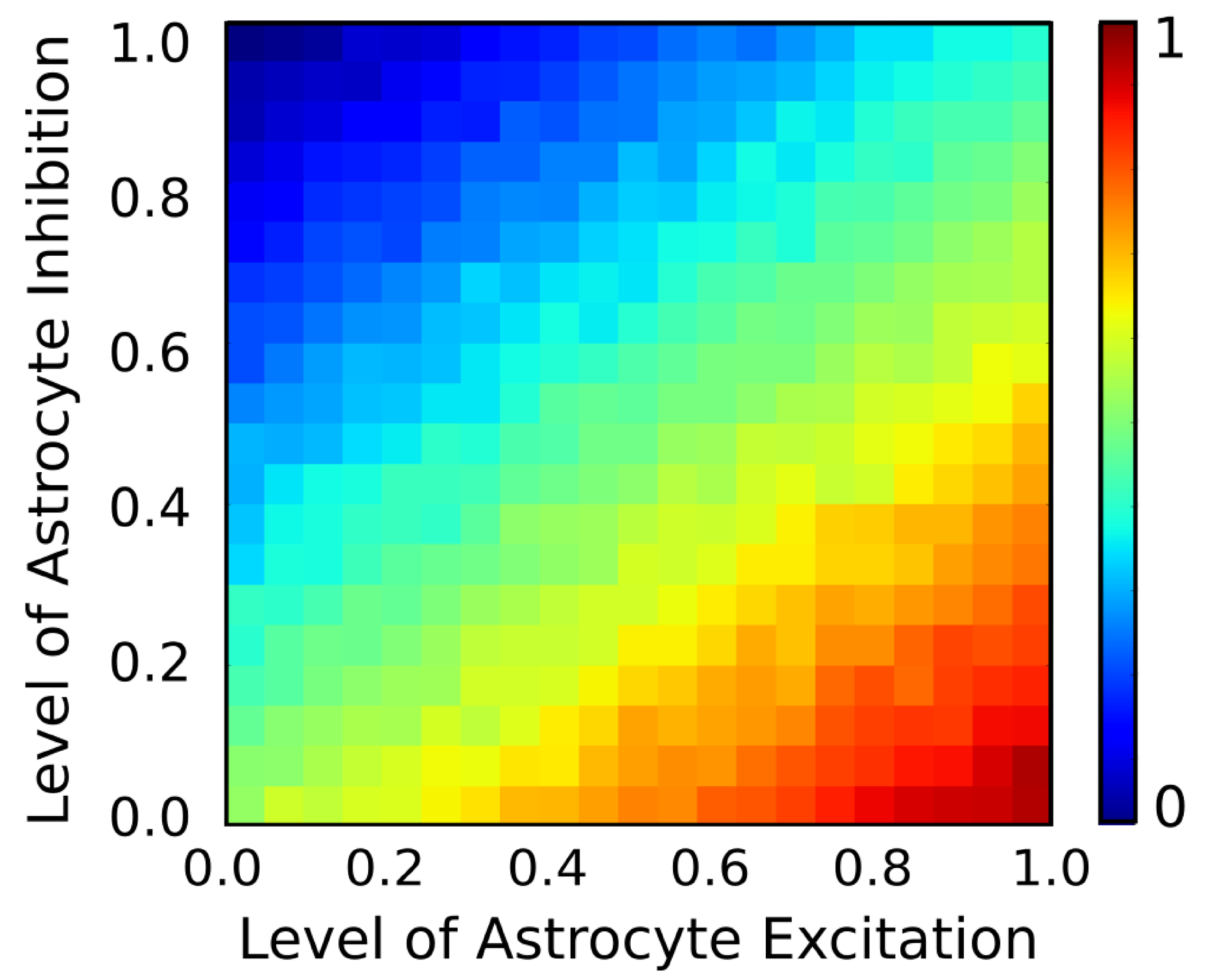

Table 1

Astrocyte Calcium Dynamics

$$c_i(r_i,t) = a_0 * \exp\left(-\frac{i}{\tau_d}\right) exp\left(-\frac{r_i - \mu\cdot v\cdot t}{\tau_{decay}}\right) - exp\left(-\frac{r_i - \mu\cdot v\cdot t}{\tau_{rise}}\right)$$

LIF Neuron Input

$$I_{total}(t) = I_{syn} + I_{SIC}$$

Synaptic Dynamics

$$\frac{df}{dt} = \left(-\frac{f}{\tau_{Ca}}\right) + (1-f)\cdot\kappa\Theta([Ca^{2+}] - [Ca^{2+}_{thresh}])$$

$$\frac{dx}{dt} = \frac{z}{\tau_{rec}} - (1-f)\cdot u\cdot x\cdot\delta(t - t_{sp}) - x * \eta(f)$$

$$\frac{dy}{dt} = -\frac{y}{\tau_{in}} + (1-f)\cdot u\cdot x\cdot\delta(t - t_{sp}) + x * \eta(f)$$

$$\frac{dz}{dt} = \frac{y}{\tau_{in}} - \frac{z}{\tau_{rec}}$$

$$I_{syn}(t) = A * y(t)$$

Slow-Inward Current Dynamics

$$w = [Ca^{2+}] - 196.11$$

$$I_{astro} = 2.11\cdot ln(w)\cdot\Theta(ln(w))$$

$$I_{SIC}(t) = I_{astro}([Ca^{2+}] = [Ca^{2+}_{peak}]_i) *$$
$$* n * \left(exp\left(-\frac{t}{\tau^{SIC}_{decay}}\right) - exp\left(-\frac{t}{\tau^{SIC}_{rise}}\right)\right)$$

Fig 1. The architecture of our proposed astrocyte-neuron model a. The characteristic tiling pattern of astrocytes in the brain. The Ca2+ wave progenitor astrocyte in denoted in black. b. The synaptic island organization of astrocyte-neuron networks. An astrocyte for a given layer entirely envelops up to eight neurons and is associated with up to 10^5 tripartite synapses c. An astrocyte-astrocyte gap junction; d. A tripartite synapse.

Fig. 2. The ability of the astrocyte layer to modulate the firing rate of the neural network. Network firing rate is normalized.

Table 1. Equations describing the interaction between a pre- and a post-synaptic neuron, under the influence of an astrocyte.

INTRODUCTION

Astrocytes connect via gap junctions to form functional networks which transmit information using intercellular Ca^{2+} waves. By simulating these waves, as well as their effect on nearby neurons, we show that the 'slow' activity of astrocytes is sufficient to modulate the 'fast' spiking activity of neurons in easily controllable ways.

MODEL

The biomimetic model consisted of LIF neurons organized into all-to-all feedforward synaptic islands (Fig 1b) [1], defined by the territory of a single astrocyte. The astrocyte-network propagated calcium waves with speed and shape taken from the literature [2]. By controlling at most two parameters—the gating function , f, and the slow-inward-current amplitude, I_{astro} (Fig 2), we were able to produce a wide range of easily tunable neural firing patterns.

CONCLUSION

The theoretical benefit of parallel processing on different temporal and spatial scales is an open question in computational brain science: Our model aims to tackle this problem by combining the fast spiking of neurons with the comparatively slow calcium activity of astrocytes. Although our understanding of neural-astrocyte dynamics is still in its infancy, translating the new "bottom-up" knowledge of astrocytic function into artificial intelligence is a promising research area [3].

REFERENCES

[1] Halassa, M. M., et al. (2007). "Synaptic islands defined by the territory of a single astrocyte." The Journal of Neuroscience **27**(24): 6473-6477.

[2] Goldberg, M., et al. (2010). "Nonlinear gap junctions enable long-distance propagation of pulsating calcium waves in astrocyte networks." PLoS Comput Biol **6**(8): e1000909.

[3] Porto-Pazos, A. B., et al. (2011). "Artificial astrocytes improve neural network performance." PLoS One **6**(4): e19109.