УНИВЕРСИТЕТ
ЛОБАЧЕВСКОГО

НЕЙРОМОРФНЫЕ МОДЕЛИ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

Сусанна Гордлеева

д.ф.-м.н., доцент,

руководитель центра нейроморфных вычислений ИТ-кампуса НЕЙМАРК

проф. каф. нейротехнологий, директор НИИ нейронаук ННГУ

gordleeva@neuro.nnov.ru

НЕЙМАРК

СЛОЖНОСТЬ МОДЕЛЕЙ

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

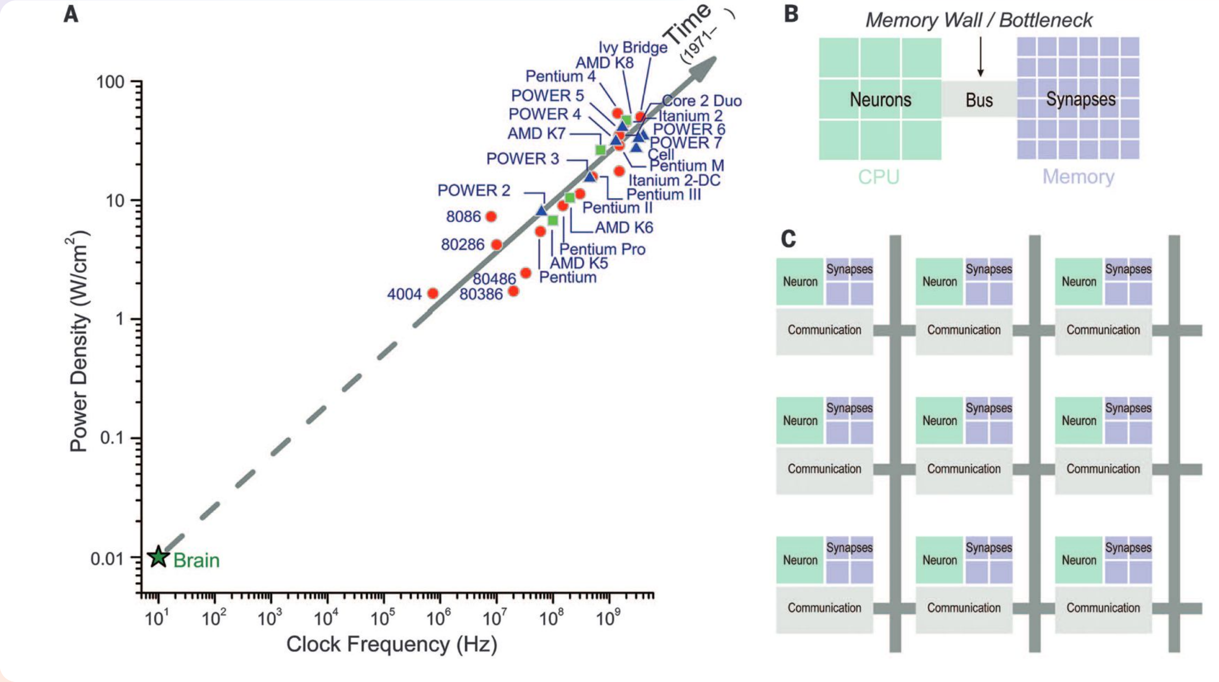

Fig. 1. Computation, communication, and memory. (**A**) The parallel, distributed architecture of the brain is different from the sequential, centralized von Neumann architecture of today's computers. The trend of increasing power densities and clock frequencies of processors (*29*) is headed away from the brain's operating point. Number and POWER processors are from IBM, Incorporated; AMD, Advanced Micro Devices, Incorporated; Pentium, Itanium, and Core 2 Duo, Intel, Incorporated. (**B**) In terms of computation, a single processor has to simulate both a large number of

of memory, the von Neumann bottleneck (*15*), which is caused by separation between the external memory and processor, leads to energy-hungry data movement when updating neuron states and when retrieving synapse states. In terms of communication, interprocessor messaging (*25*) explodes when simulating highly interconnected networks that do not fit on a single processor. (**C**) Conceptual blueprint of an architecture that, like the brain, tightly integrates memory, computation, and communication in distributed modules that operate in parallel and communicate via an event-driven network.

СЛОЖНОСТЬ МОДЕЛЕЙ

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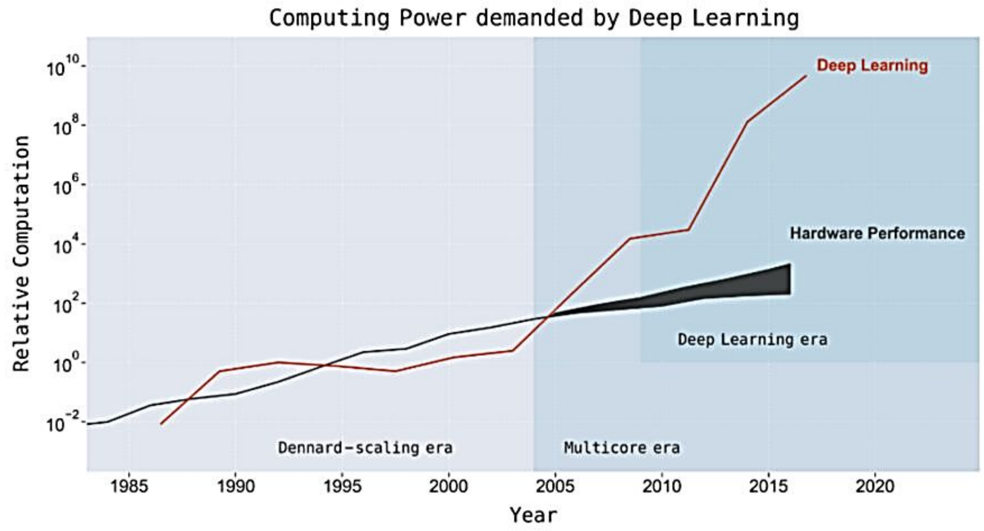
ChatGPT

Toutefois, l'université de Californie a fait les calculs et estime que **l'entraînement** seul de **l'IA** pour **GPT-3** a consommé **1 287 MWh** qui ont émis **552 tonnes** de CO2e, soit plus de **205 vols aller-retourentre Paris et New-York**.



"The Computational Limits of Deep Learning" by N. Thompson, et al. (2020)

https://incrypted.com/chat-gpt-potratil-energiyu-kak-na-majning-111-btc/

https://www.hellowatt.fr/blog/chat-gpt-empreinte-carbone/

https://towardsdatascience.com/chatgpts-electricity-consumption-7873483feac4

https://ai.stackexchange.com/questions/38970/how-much-energy-consumption-is-involved-in-chat-gpt-responses-being-generated

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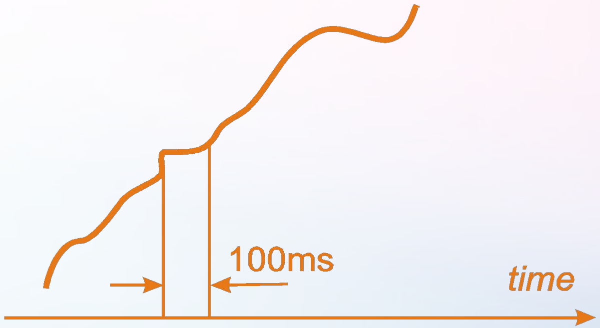
ЕСТЕСТВЕННЫЙ ИИ VS ИСКУССТВЕННЫЙ ИИ

Выживание организма в природе в процессе эволюции требует высочайшей моторной координации

Welsh and Llinas, 1997

Управление мышцами



Тактовая частота 10 Гц
Энергопотребление 10 Вт

50 групп мышц → 10^{15} различных комбинаций → Для решения задачи требуется процессор с тактовой частотой 10^{6} Ггц

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НЕЙРОМОРФНЫЕ СИСТЕМЫ

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

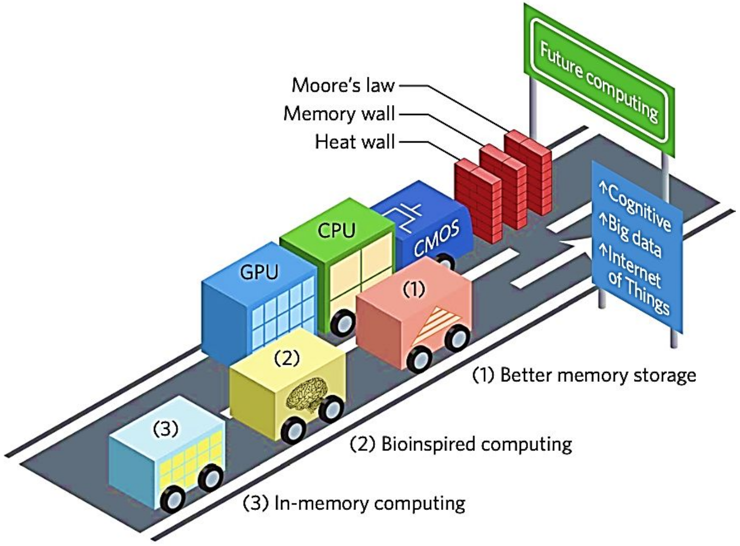
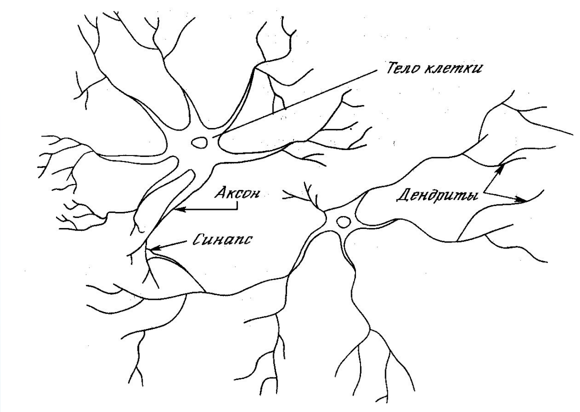


Fig. 1 | The race towards future computing solutions. Conventional computing architectures face challenges including the heat wall, the memory wall and the end of Moore's law. Developments in memristor technology may provide an alternative path that enables hybrid memory–logic integration, bioinspired computing and efficient reconfigurable in-memory computing systems. CMOS, complementary metal–oxide–semiconductor; GPU, graphics processing unit; CPU, central processing unit.

https://www.nature.com/articles/s41928-017-0006-8



Карвер Мид

В 1990 году ввел термин Neuromorphic Electronic Systems

“Biological solutions are many orders of magnitude more effective than thosewe have been able to implement using digital methods. Large-scale adaptive analog systems are more robust to component degredation and failure than are more conventional systems, and they use far less power. For this reason, adaptive analog technology can be expected to utilize the full potential of water-scale silicon fabrication.”

НЕЙРОМОРФНЫЕ СИСТЕМЫ

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
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TrueNorth (2014)

~1M нейронов
4096 ядер
28 нм
430 мм2
~256M синапсов
~65мВт

Loihi-2 (2021)

~1M нейронов
128 ядер
7 нм
31 мм2
~67M синапсов
~200 мВт

Tianjic (2021)

~ 40К нейронов
156 ядер
28 нм
14,5 мм2
~10M синапсов
~950 мВт

Akida AKD1000 (2022)

~1,2M нейронов
80 ядер
28 нм
225 мм2
~10 млрд синапсов
~100мкВ-300 мВт

AltAI (2023)

~130К нейронов
256 ядер
28 нм
64 мм2
~67M синапсов
~100-500 мВт

NorthPole (2023)

? нейронов
256 ядер
12 нм
? мм2
? синапсов
?12 Вт

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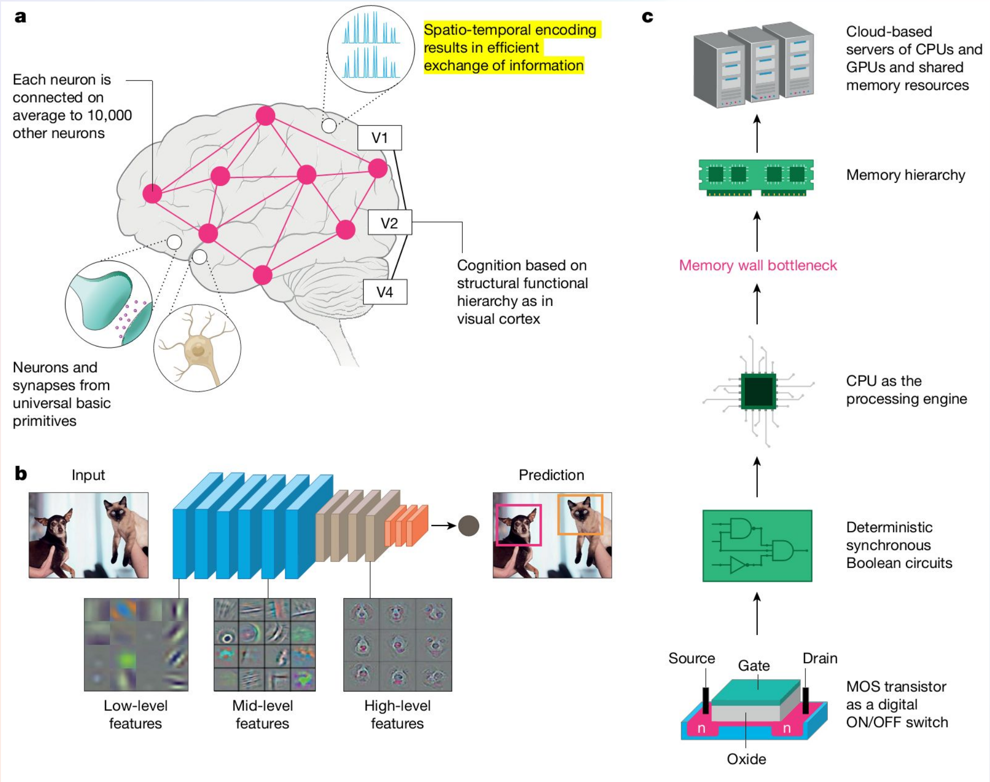
НЕЙРОМОРФНЫЙ ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ



Разработка новых технологий искусственного интеллекта на основе биологически релевантных моделей нейронных сетей, реализующих принципы обработки информации в мозге

НЕЙМАРК

ТИПЫ КЛЕТОК МОЗГА

НЕЙРОНЫ

Передача, обработка и хранение информации

ГЛИАЛЬНЫЕ КЛЕТКИ

Питание, обеспечение нейронов, сигнальная функция и др.

КЛЕТКИ КРОВЕНОСНЫХ СОСУДОВ

Питание мозга нутриентами и кислородом
Добавка БАВ
Часть ГЭБ

НЕЙМАРК

НЕЙРОН

Сома или тело

Диаметр сомы 100 мкм и более, у самых мелких – 5 мкм

Дендриты

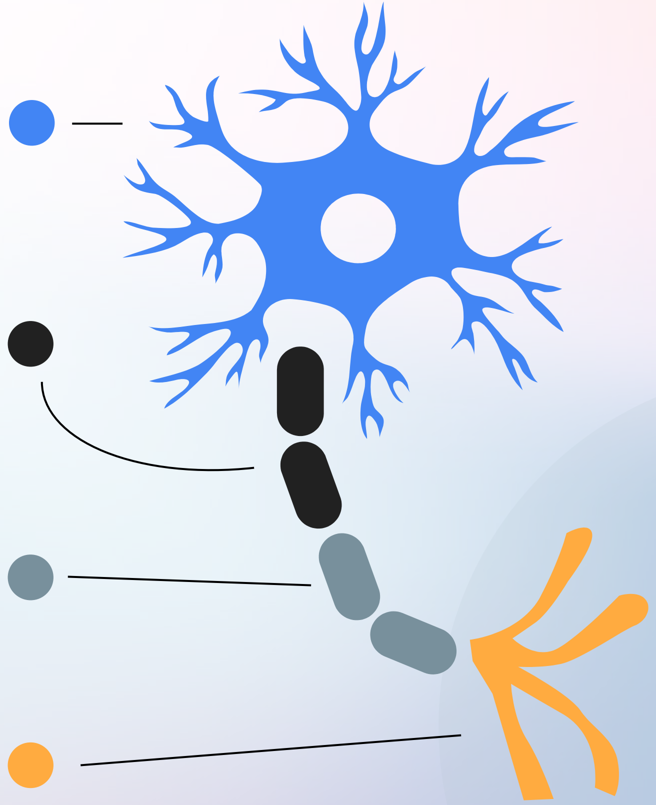
Выросты, которые обеспечивают пространственную локализацию нейрона. На них располагаются синапсы с другими нейронами. Некоторые дендриты имеют «шипики», которые являются постсинаптической частью

Аксон

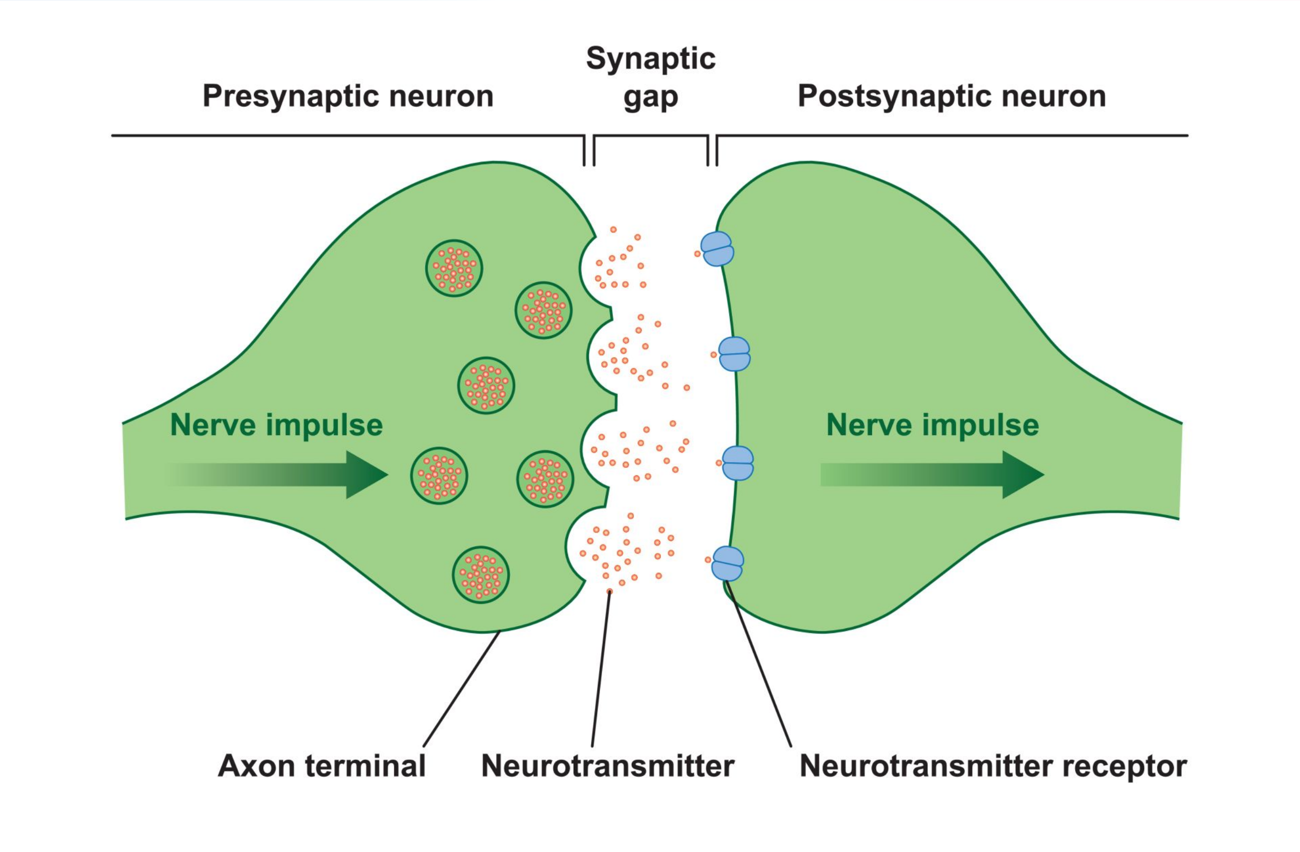
Удлиненный вырост структурно и функционально приспособленный для передачи потенциала действия. Может иметь миелиновую оболочку

Аксональные пресинаптические терминали

Отвечают за передачу информации



КАК НЕЙРОНЫ МЕЖДУ СОБОЙ ОБЩАЮТСЯ?

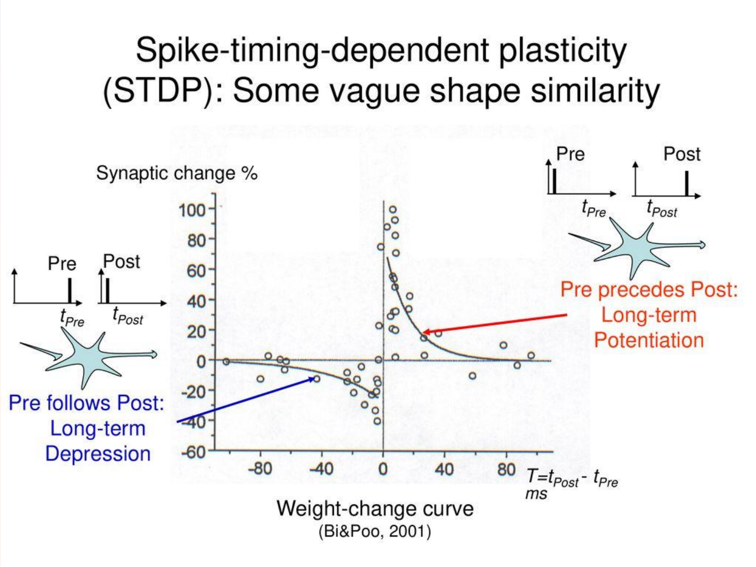


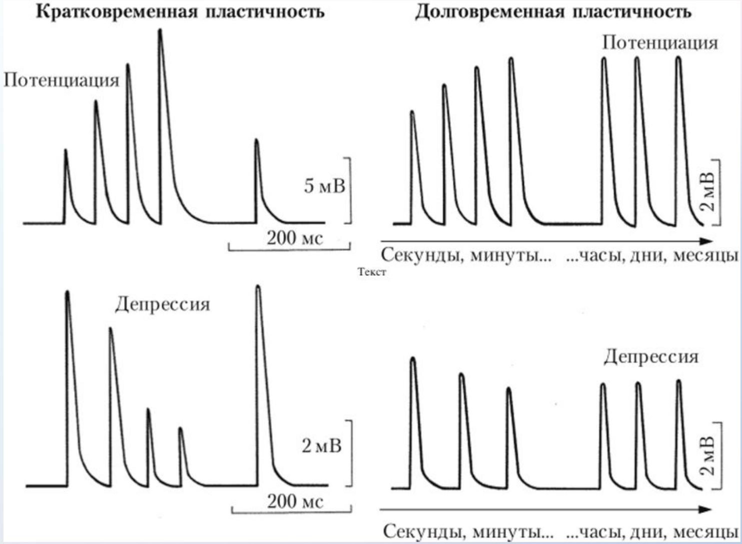
НЕЙМАРК

КАК НЕЙРОНЫ МЕЖДУ СОБОЙ ОБЩАЮТСЯ?

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

Согласно **STDP-правилу**, изменения в эффективности связи происходят при близкой во времени генерации импульсов на пресинаптическом (нейроне-передатчике) и постсинаптическом (нейроне-приёмнике) нейроне: связь усиливается, если импульс на пресинапсе опережает импульс на постсинапсе, и ослабляется в обратном случае.

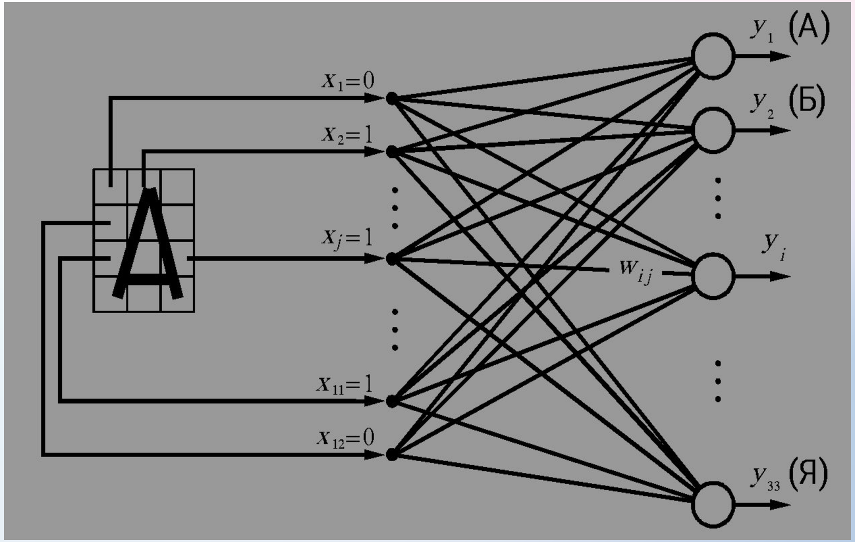




ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ

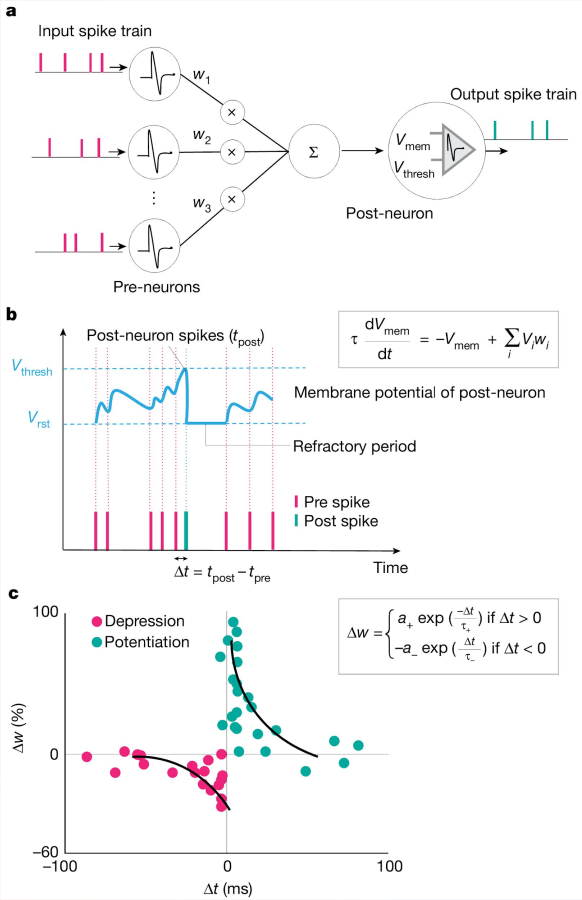
Герберт Саймон

Тот кто, владеет Искусственным Интеллектом – то станет **Властелином Мира**!

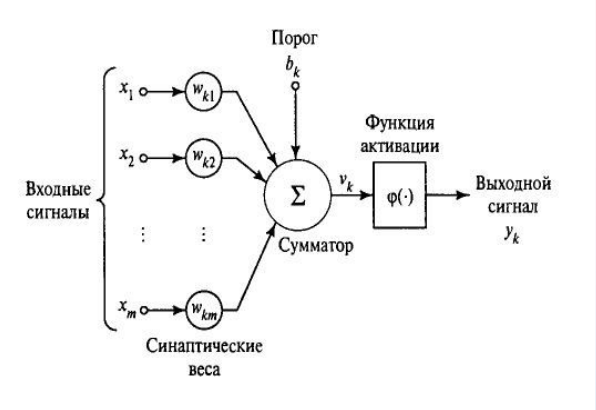


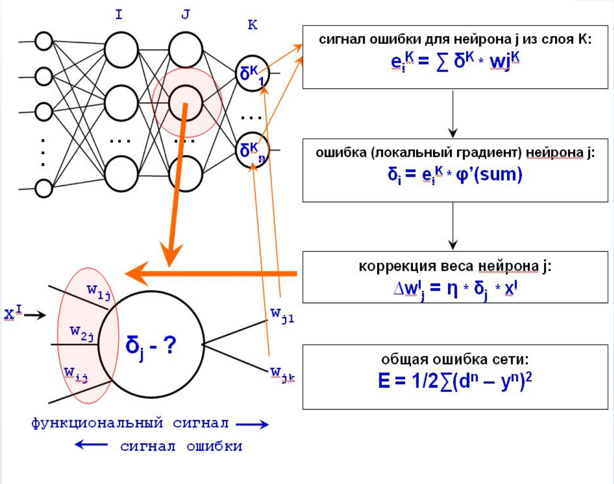
Фрэнк Розенблатт

LEARNING IN SNN. ANN versus SNN



STDP





BackProp

НЕЙМАРК

МОЗГ И ИИ

Механизмы реализации информационных (когнитивных) функций

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
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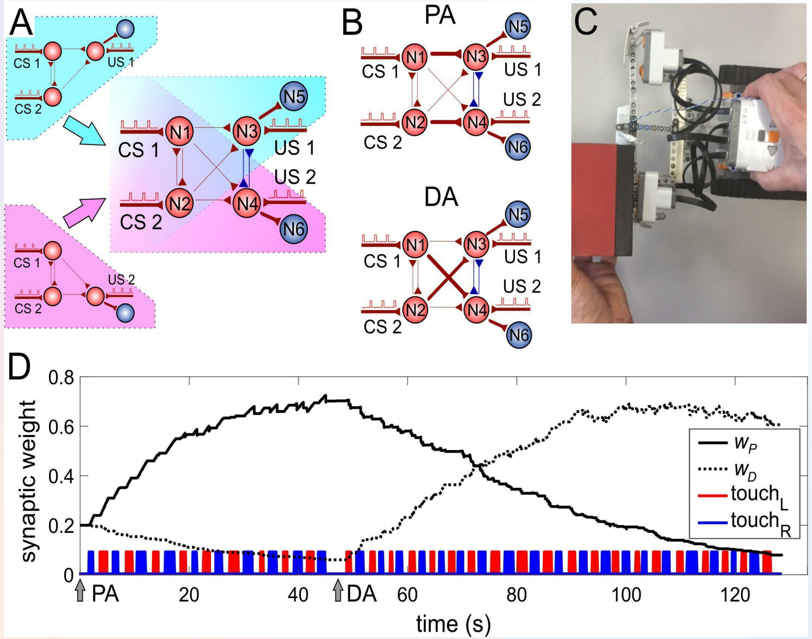
Нейрон
аналоговый элемент с собственной нетривиальной динамикой

- Нейронная сеть формируется за счет синаптических связей с пластичностью
- Нейронные сети мозга структурированы – обладают определенной архитектурой
- Архитектура сети пластична (rewiring)
- Число элементов сети (нейронов и синапсов) – динамически изменяемо
- Нейронная сеть обучается в интерфейсе с исполнительными устройствами

Формальный нейрон
алгебраическая функция с бинарным выходом

- Искусственная нейронная сеть (ИНС) формируется за счет направленных связей с настраиваемым весом
- ИНС имеют слоистую структуру
- Архитектура сети статична
- Число элементов сети фиксировано (в редких случаях могут добавляться нейроны при обучении)

ASSOCIATIVE LEARNING IN SNNs

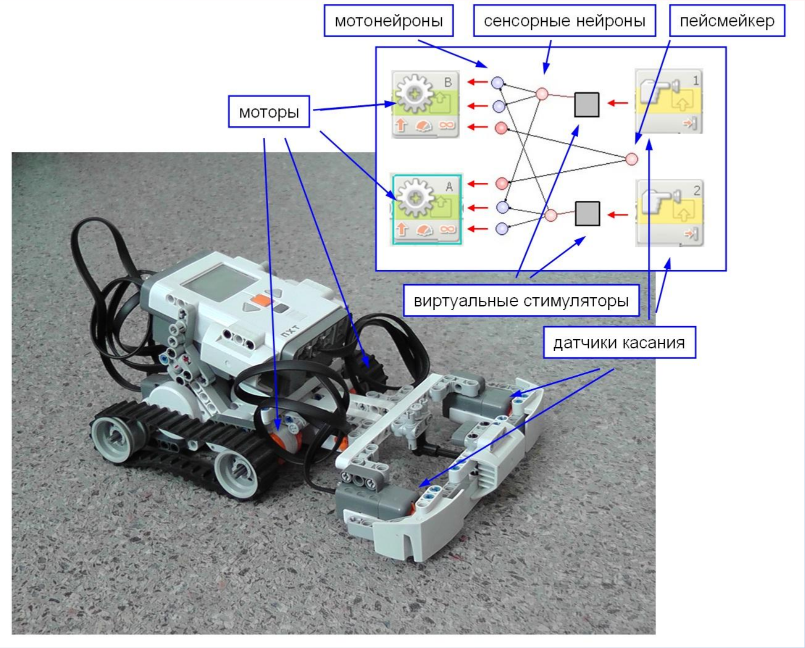



frontiers in Neuroscience

ORIGINAL RESEARCH
published: 26 February 2020
doi: 10.3389/fnins.2020.00088

Spatial Properties of STDP in a Self-Learning Spiking Neural Network Enable Controlling a Mobile Robot

Sergey A. Lobov[1,2*], Alexey N. Mikhaylov[1], Maxim Shamshin[1], Valeri A. Makarov[1,3] and Victor B. Kazantsev[1,2]



Robot under control of spiking neural network with conditional learning

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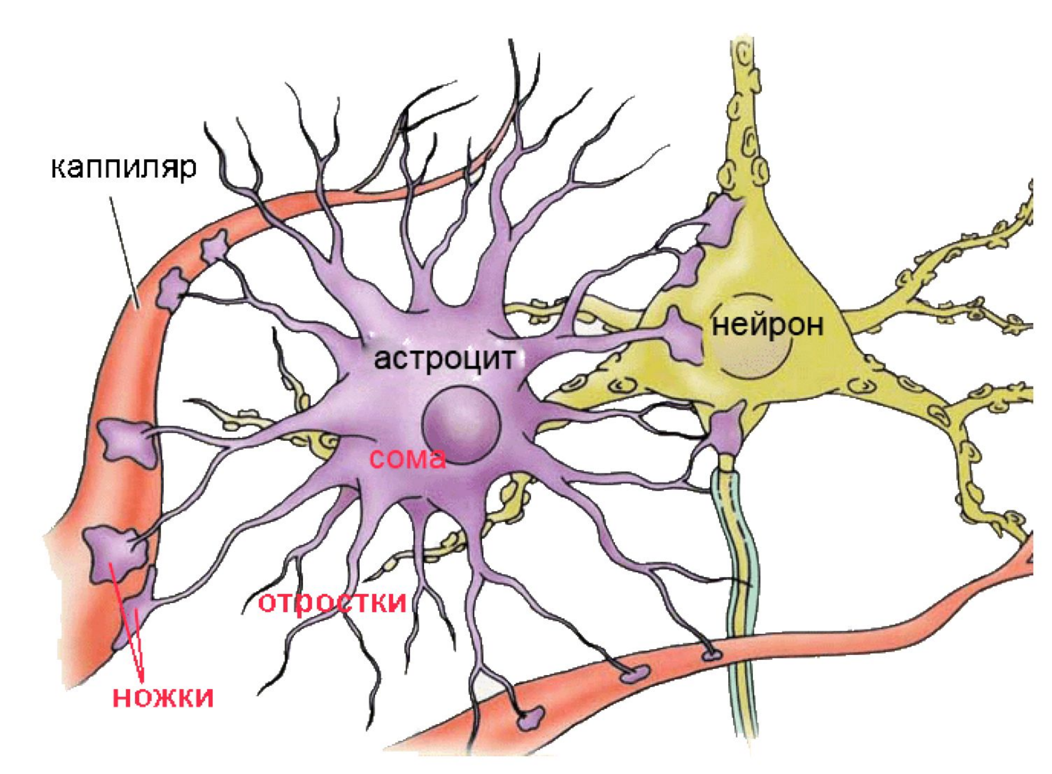
АСТРОЦИТЫ



Функции:

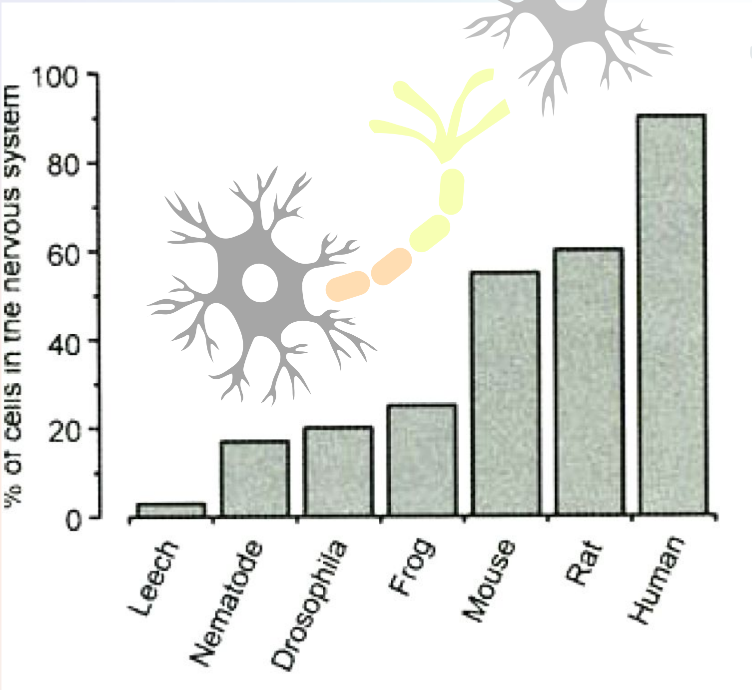
– Гомеостатическая, то есть поддержание ионного и химического состава среды

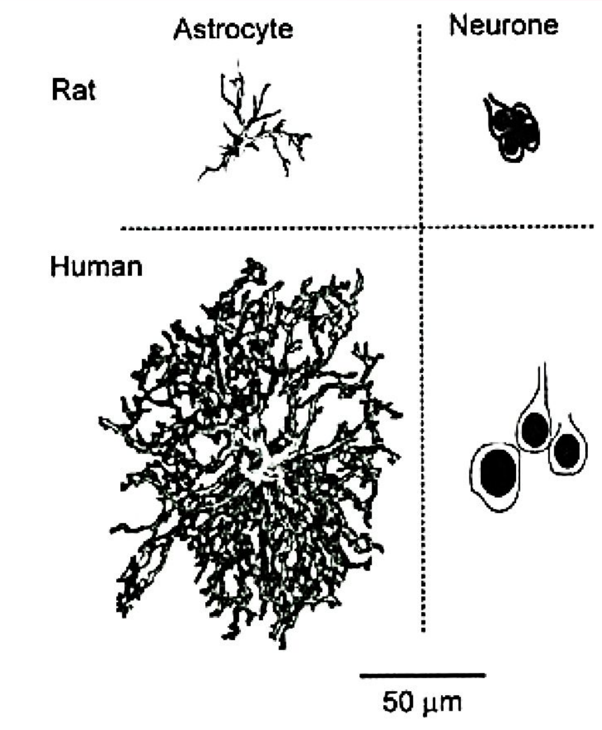
– Метаболическая, то есть синтез и разложение веществ

– Сигнальная – передача сигнала

– Трофическая, то есть влияние на рост и развитие нейронов

НЕЙРОНЫ, ГЛИЯ И ОРГАНИЗАЦИЯ МОЗГА





НЕЙРОНЫ, ГЛИЯ И ОРГАНИЗАЦИЯ МОЗГА

Университет Лобачевского
Нижегородский государственный университет

Мозг Эйнштейна

Увеличение сложности отростков астроцитов

BRAIN RESEARCH REVIEWS 52 (2006) 257–263

available at www.sciencedirect.com

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BRAIN RESEARCH REVIEWS

Review

Cerebral cortex astroglia and the brain of a genius: A propos of A. Einstein's

Jorge A. Colombo[a,], Hernán D. Reisin[a], José J. Miguel-Hidalgo[b], Grazyna Rajkowska[b]*

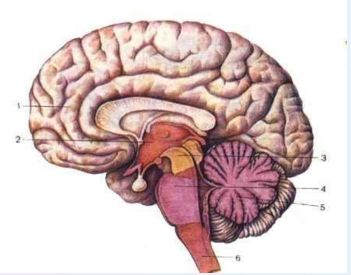
[a]Unidad de Neurobiología Aplicada (UNA) (CEMIC-CONICET), Av. Galván 4102, C1431FWO Ciudad de Buenos Aires, Argentina
[b]Division of Neurobiology and Behavior Research, Department of Psychiatry, University of Mississippi Medical Center, Jackson, MS 39216, USA

НЕЙМАРК

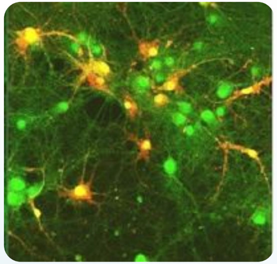
НЕЙРОН-АСТРОЦИТАРНЫЕ СЕТИ

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

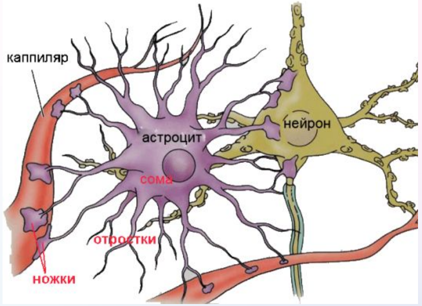
Brain



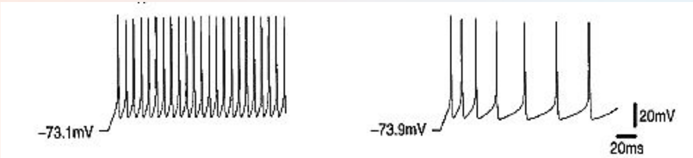
Neuron-astrocytic networks



Neuron-astrocyte interaction

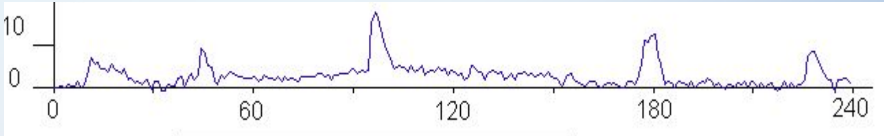


Neurons being the main signal cells of the brain provide the transmission and transformation of sequences of electrical pulses in a neural network.
Astrocytes are not electrically excitable cells. Astrocytes display a form of cellular excitability based on variations of the Ca^{2+} concentration in the cytosol.



Electrical activity in neurons (1 ms)

Izhikevich E.M. Dynamical Systems. The MIT press, 2007



Ca^{2+} - activity in astrocyte (1 s)

НЕЙМАРК

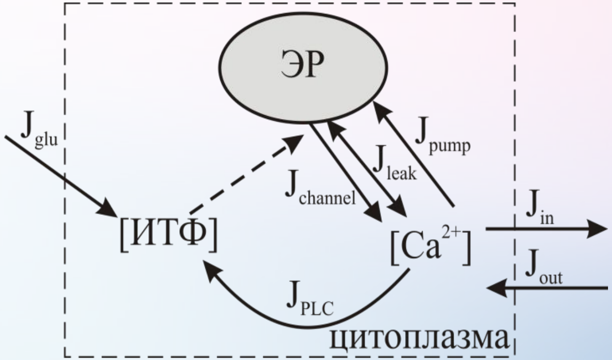
МОДЕЛЬ КАЛЬЦИЕВОЙ СИГНАЛИЗАЦИИ В АСТРОЦИТАХ

Ca^{2+}-induced Ca^{2+} release (CICR) from the astrocyte's endoplasmic reticulum stores, which depends on cytosolic concentration of the second messenger inositol 1,4,5-trisphosphate (IP_3)

$$\frac{dIP3}{dt} = \frac{IP3^* - IP3}{\tau_{IP3}} + J_{PLC} + J_{glu},$$

$$\frac{dCa}{dt} = J_{channel} - J_{pump} + J_{leak} + J_{in} - J_{out},$$

$$\frac{dz}{dt} = a_2\left(d_2 \frac{IP3 + d_1}{IP3 + d_3}(1 - z) - z * IP3\right),$$



$IP3$ – intracellular concentration of inositol 1,4,5-trisphosphate,
Ca – intracellular concentration of free calcium ions in the cytosol,
Z – Ca^{2+}-mediated deinactivation of IP_3 receptor/Ca^{2+} channels on the ER.

$$J_{channel} = c_1 v_1 IP3^3 Ca^3 z^3 \left(\frac{c_0}{c_1} - \left(1 + \frac{1}{c_1}\right)Ca\right) / \left[(IP3 + d_1)(Ca + d_5)\right]^3,$$

$$J_{PLC} = v_4 (Ca + (1 - \alpha) k_4) / (Ca + k_4),$$

$$J_{leak} = c_1 v_2 \left(\frac{c_0}{c_1} - \left(1 + \frac{1}{c_1}\right)Ca\right),$$

$$J_{pump} = v_3 Ca^2 / (k_3^2 + z^2),$$

$$J_{in} = v_5 + v_6 IP3^2 / (k_2^2 + IP3^2), \qquad J_{out} = k_1 Ca,$$

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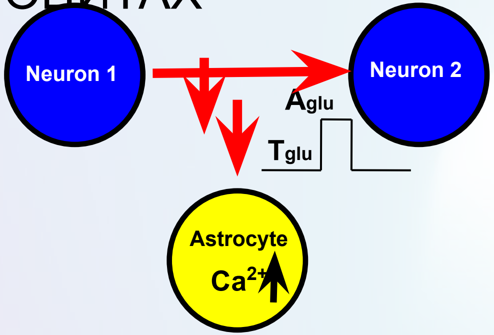
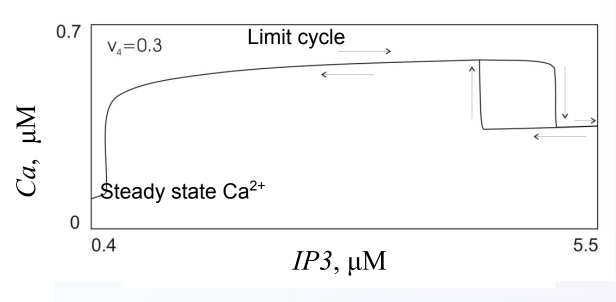
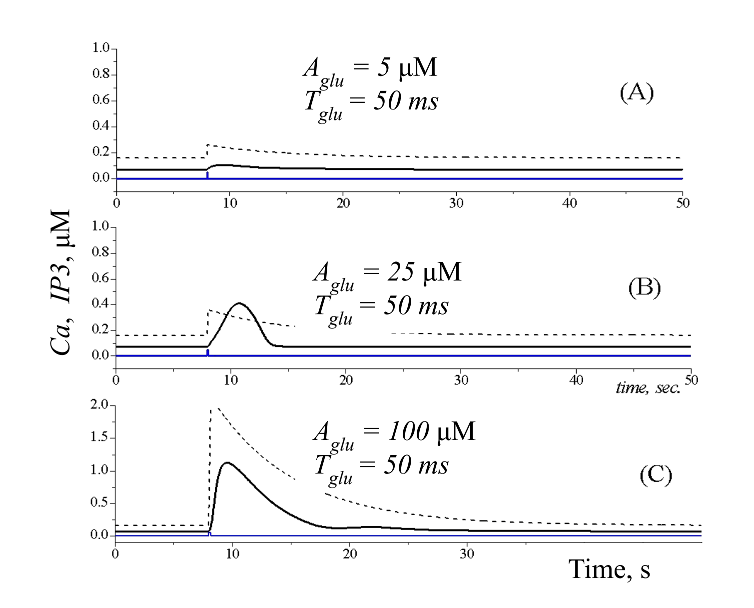
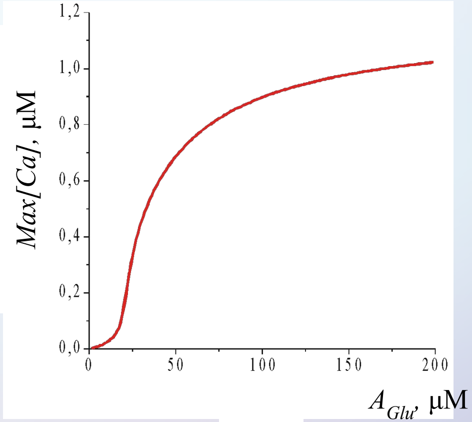
КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ









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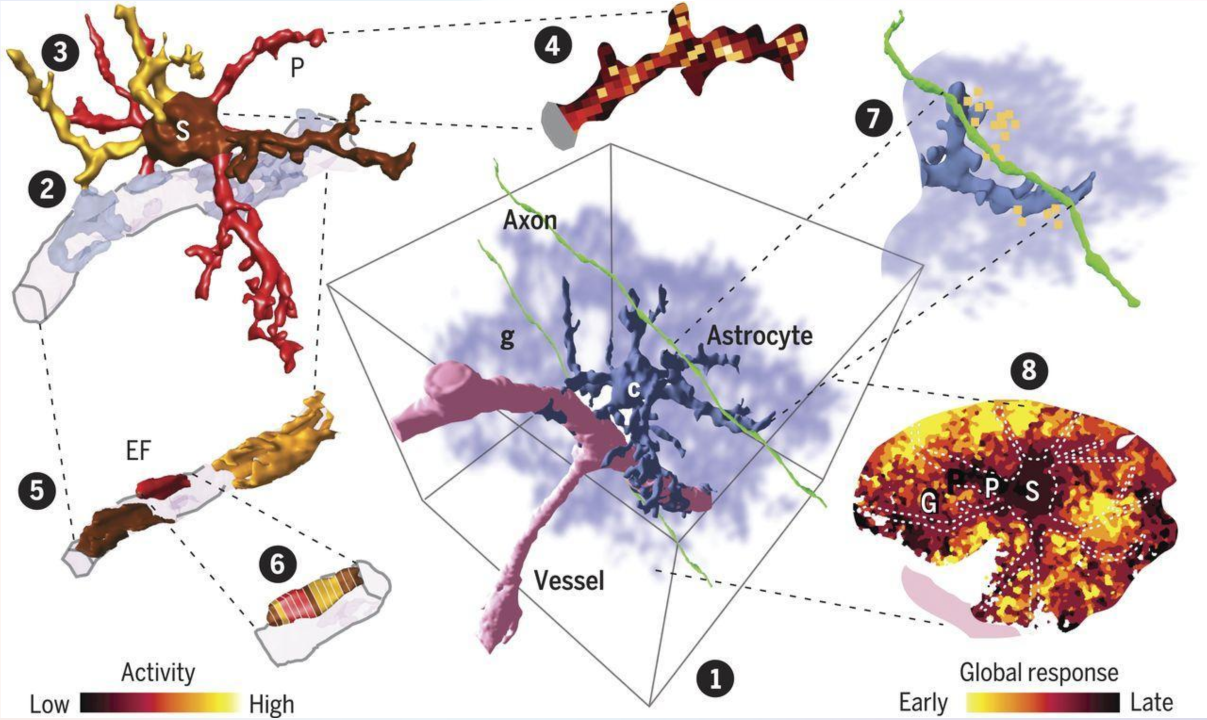
ВНУТРИКЛЕТОЧНАЯ КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ

New experimental approaches to study the signaling of astrocytes at qualitatively new spatial-temporal resolutions show that astrocytic Ca^{2+} activity in processes and soma is highly heterogeneous.

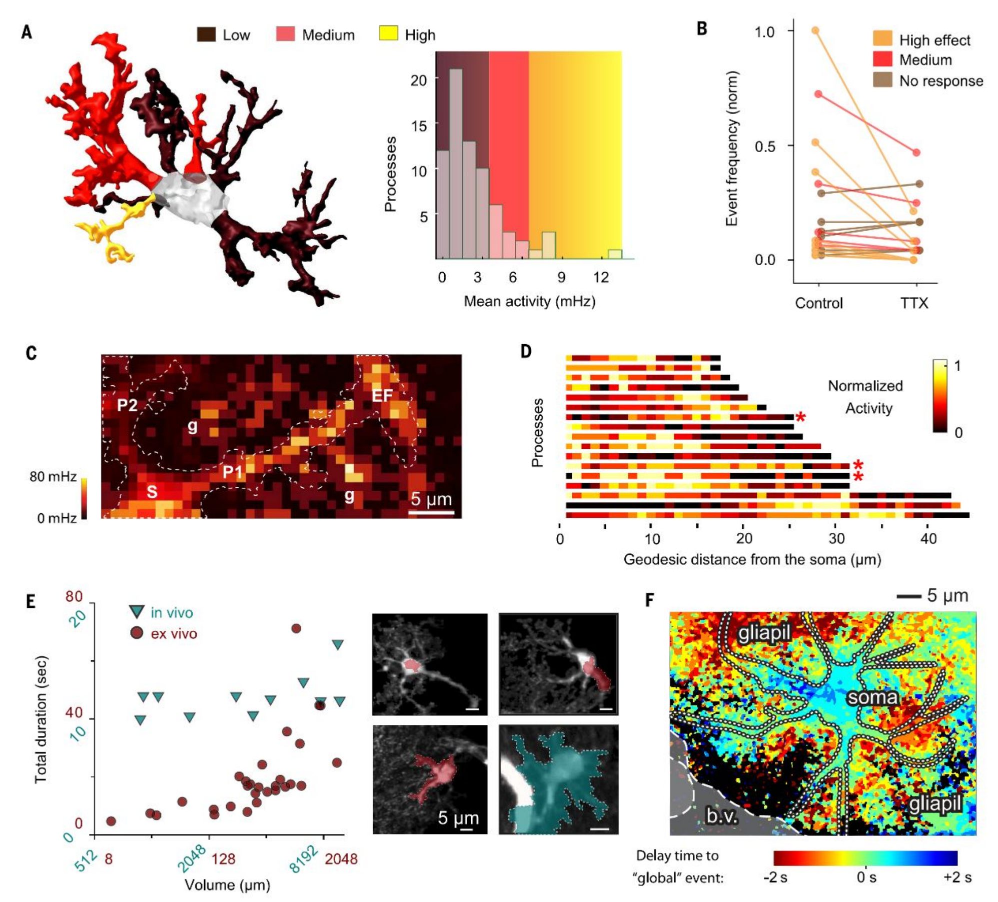


E. Bindocci et al. Science 2017

НЕЙМАРК

ВНУТРИКЛЕТОЧНАЯ КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

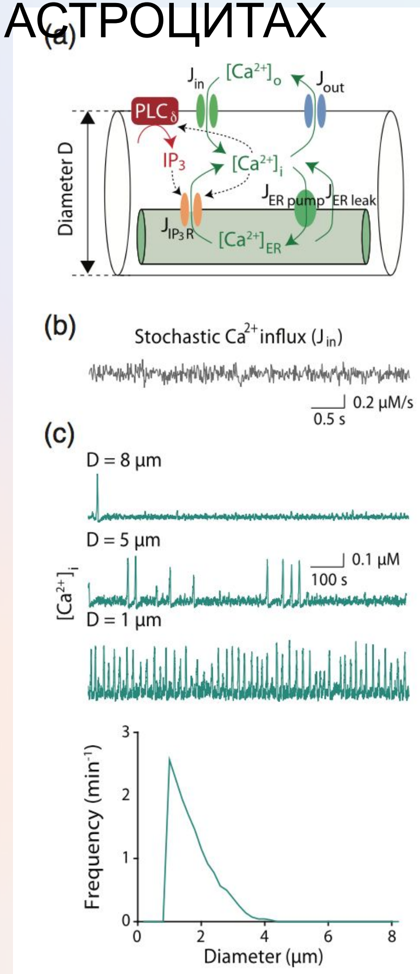


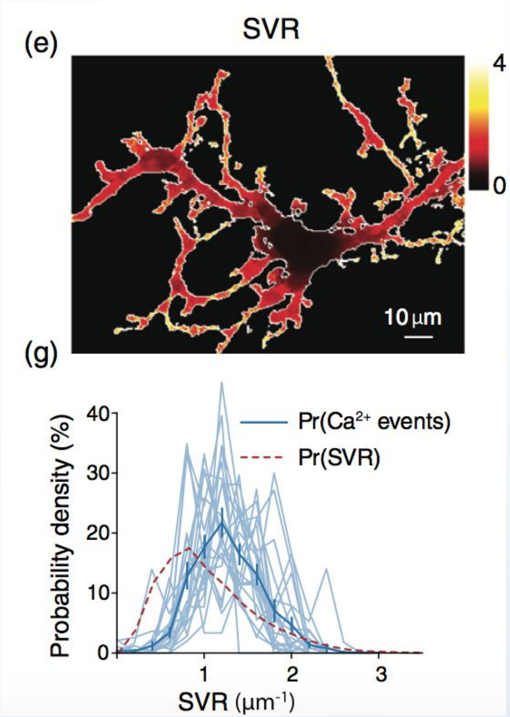
Astrocyte Ca^{2+} signaling is characterized by a complex spatial-temporal profile ranging from small, local fast responses to larger, global but slower responses that result from the integration of signals derived from restricted regions of processes close to synapses.

E. Bindocci et al. Science 2017

НЕЙМАРК

ВНУТРИКЛЕТОЧНАЯ КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ





To investigate the mechanisms underlying such subcellular distribution of the Ca^{2+} events we developed a model of spontaneous calcium activity in astrocytic process taken into account the geometry of the cell.

Received: 14 March 2018 | Revised: 19 August 2018 | Accepted: 3 September 2018
DOI: 10.1002/glia.23537
GLIA
WILEY

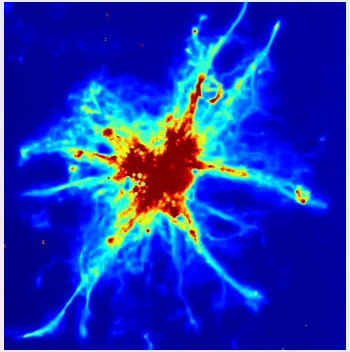
RESEARCH ARTICLE

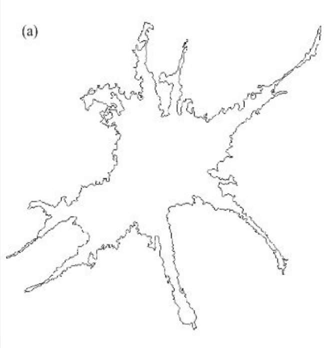
Morphological profile determines the frequency of spontaneous calcium events in astrocytic processes

Yu-Wei Wu[1,2] | Susan Gordleeva[3] | Xiaofang Tang[1] | Pei-Yu Shih[1] | Yulia Dembitskaya[1,3] | Alexey Semyanov[1,3,4,5]

ВНУТРИКЛЕТОЧНАЯ КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ

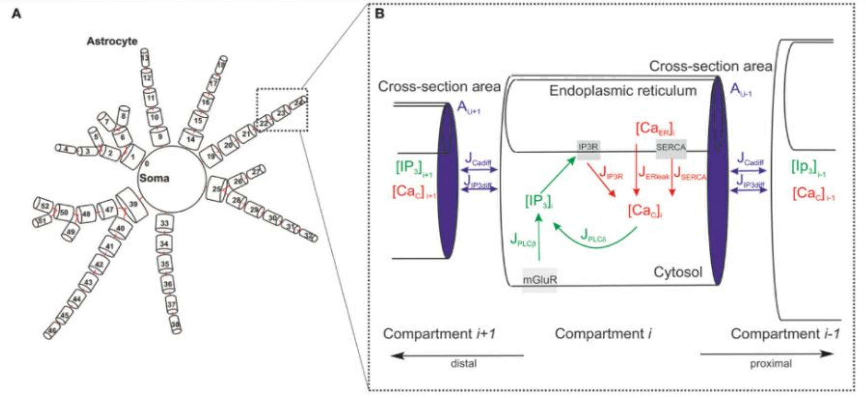
УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ





To analyze mechanisms of correlations between local signals and the global signalization response of the astrocyte including its spatially distributed structure, we propose a spatially extended model of astrocyte calcium dynamics

- Зависимость от размеров ЭР и компартмента, учет *$[Ca^{2+}]_{ER}(t)$*
(Oschmann et al., 2017)
- Детальное описание процессов деградации и производства ИТФ (De Pitta et al., 2009)
- Диффузионная связь между компартментами



$$\frac{d[Ca^{2+}]_{ij}}{dt} = \sqrt{r_{ER}}\left(J_{IP_3R} - J_{SERCA} + J_{CERleak}\right) + J_{Ca_{diff}};$$

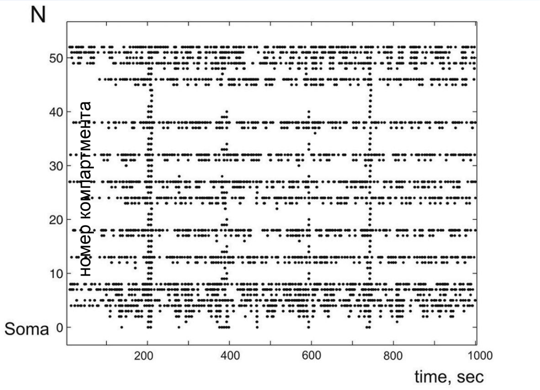
$$\frac{d[Ca^{2+}]_{ERj}}{dt} = \frac{1}{\sqrt{r_{ER}}}\left(-J_{IP_3R} + J_{SERCA} - J_{CERleak}\right) + J_{CaER_{diff}};$$

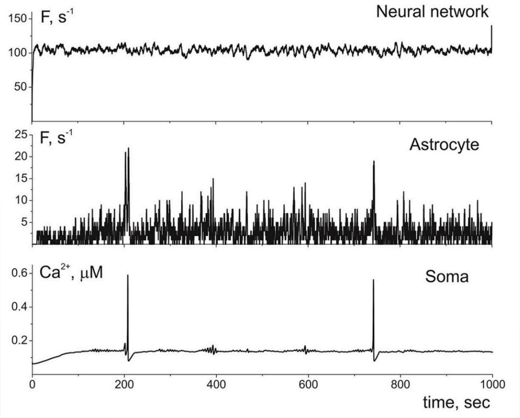
$$\frac{d[IP_3]_j}{dt} = J_{PLC\beta} + J_{PLC\delta} - J_{IP_3-3K} - J_{IP-5P} + J_{IP_3\,diff}.$$

НЕЙМАРК

ВНУТРИКЛЕТОЧНАЯ КАЛЬЦИЕВАЯ ДИНАМИКА В АСТРОЦИТАХ

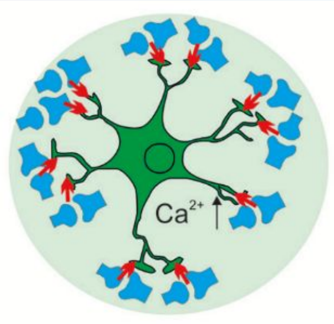
Растр Ca^{2+} активности в астроците

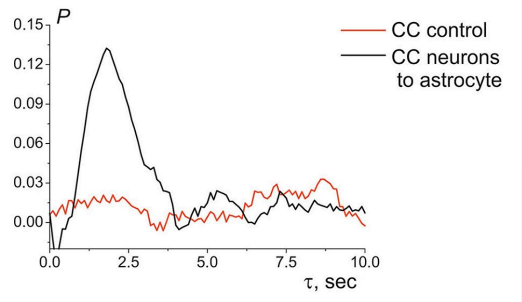




Astrocyte as Spatiotemporal Integrating Detector of Neuronal Activity

Susan Yu. Gordleeva, Anastasia V. Ermolaeva, Innokentiy A. Kastalskiy and Victor B. Kazantsev*



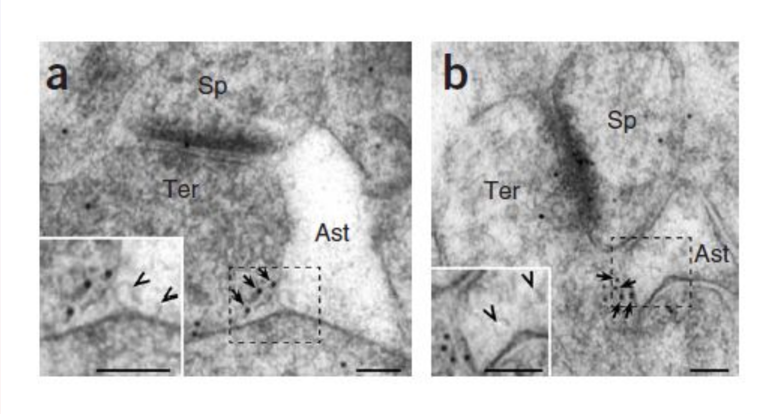


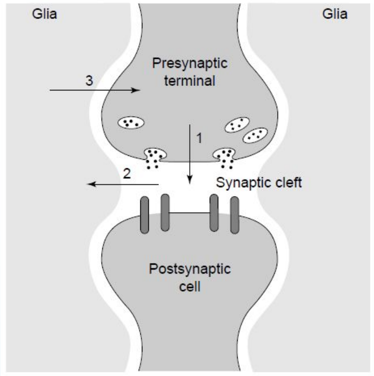
We show that astrocyte can act as temporal and spatial integrator, hence, detecting the level of spatio-temporal coherence in the activity of accompanying neuronal network

НЕЙМАРК

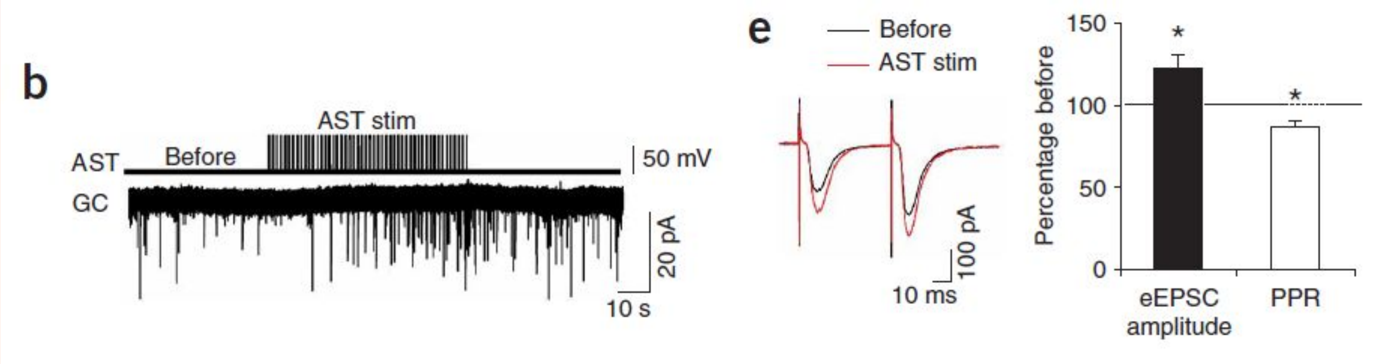
КОНЦЕПЦИЯ ТРЕХЧАСТНОГО СИНАПСА

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ





Astrocyte calcium elevations stimulate the release of different neuroactive substances—called gliotransmitters—such as glutamate, ATP and D-serine, which regulate neuronal excitability and synaptic transmission (Haydon & Araque 2002; Volterra & Bezzi 2002; Perea et al. 2009).

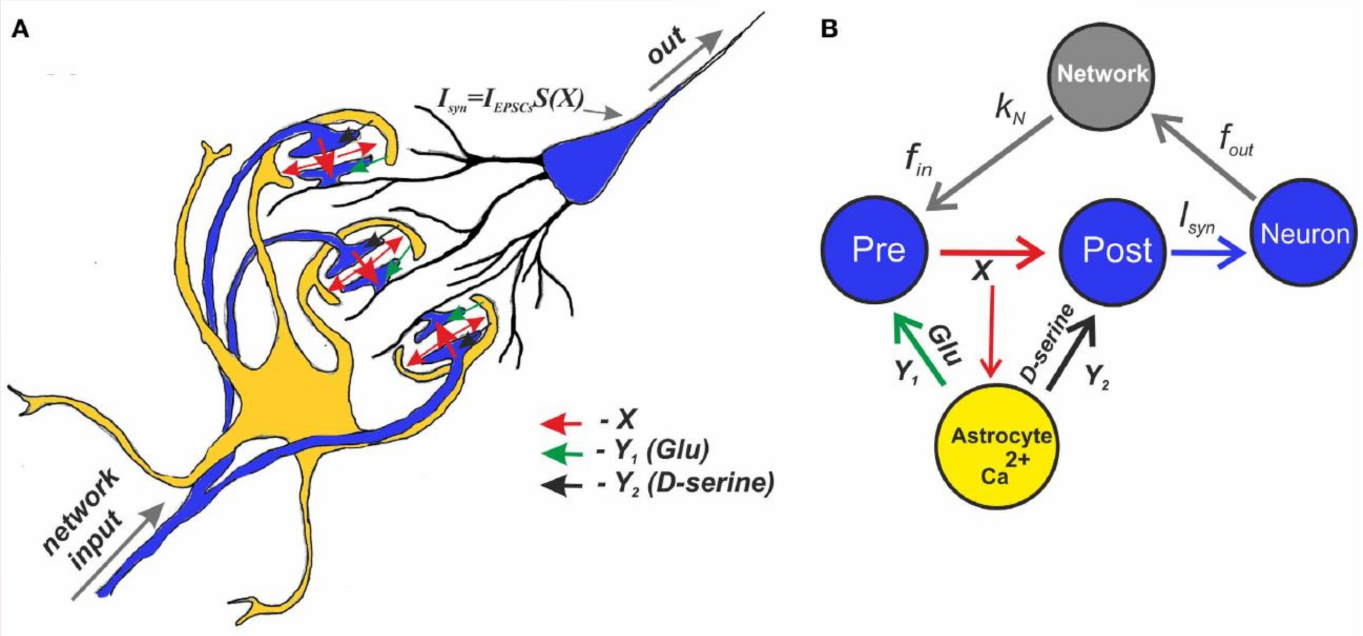


Jourdain P. et. al., Nat. Neurosci. 2007

Glutamate exocytosis from astrocytes controls synaptic strength

НЕЙМАРК

МОДЕЛЬ НЕЙРОН-АСТРОЦИТАРНОГО ВЗАИМОДЕЙСТВИЯ



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COMPUTATIONAL NEUROSCIENCE

ORIGINAL RESEARCH ARTICLE
published: 02 November 2012
doi: 10.3389/fncom.2012.00092

Bi-directional astrocytic regulation of neuronal activity within a network

S. Yu Gordleeva[1,2], S. V. Stasenko[1,2], A. V. Semyanov[2,3], A. E. Dityatev[2,4] and V. B. Kazantsev[1,2]*

[1] Laboratory of Nonlinear Dynamics of Living Systems, Institute of Applied Physics of Russian Academy of Science, Nizhny Novgorod, Russia
[2] Laboratory of Brain Extracellular Matrix Research, University of Nizhny Novgorod, Nizhny Novgorod, Russia
[3] RIKEN Brain Science Institute, Saitama, Japan
[4] Department of Neuroscience and Brain Technologies, Istituto Italiano di Tecnologia, Genova, Italy

НЕЙМАРК

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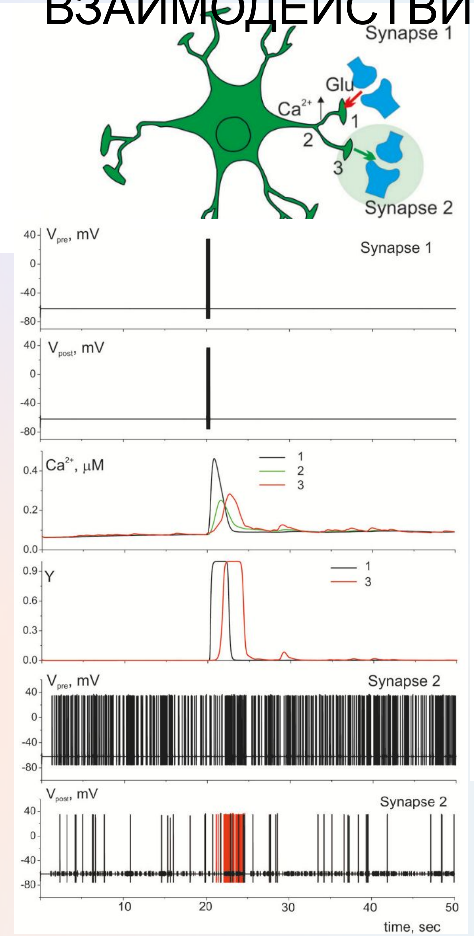
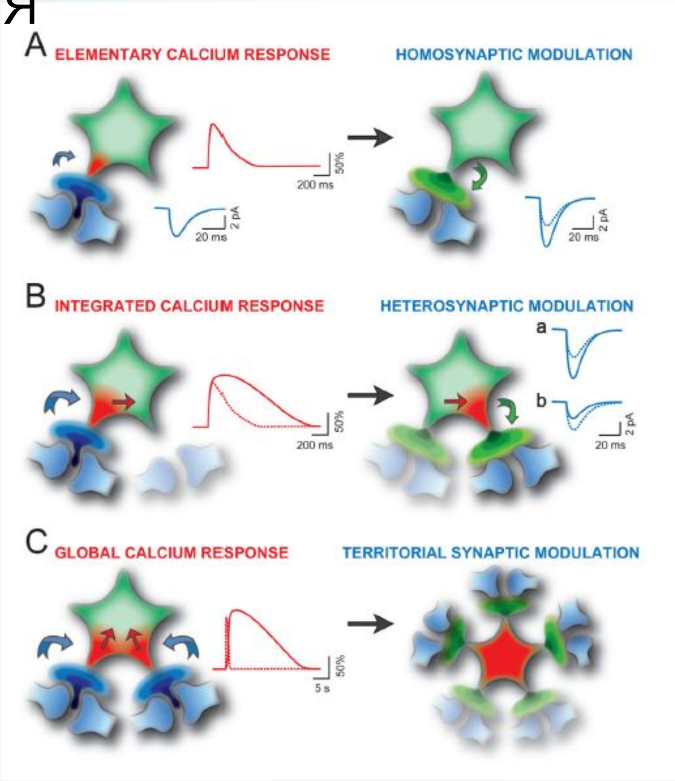
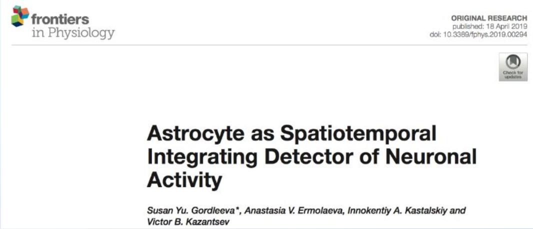




Araque et al., 2014

Different level of the neuronal activity can trigger Ca^{2+} dynamics in astrocyte with various spatio-temporal characteristics which can lead to different astrocytic-induced regulatory effects on synaptic transmission.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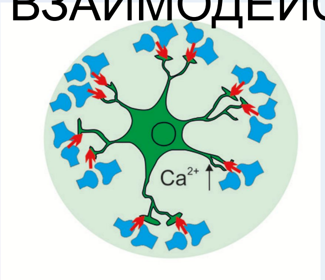
ORIGINAL RESEARCH
published: 18 April 2019
doi: 10.3389/fphys.2019.00294

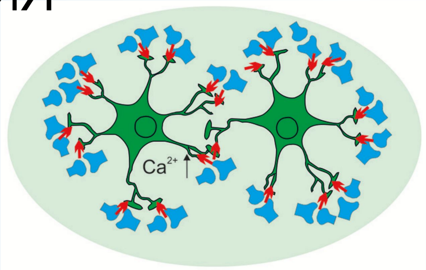
Astrocyte as Spatiotemporal Integrating Detector of Neuronal Activity

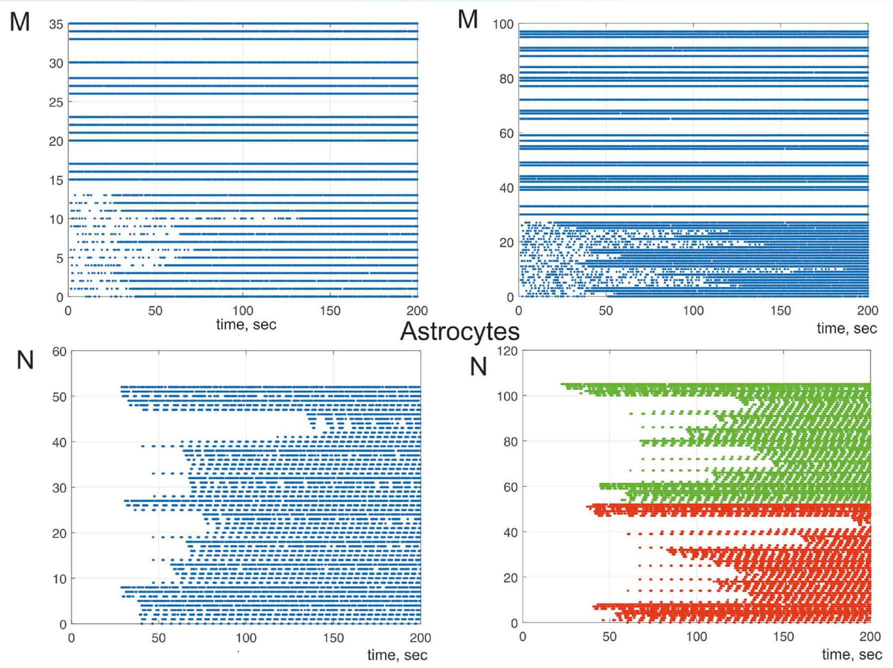
Susan Yu. Gordleeva, Anastasia V. Ermolaeva, Innokentiy A. Kastalskiy and Victor B. Kazantsev*

НЕЙМАРК

МОДЕЛЬ НЕЙРОН-АСТРОЦИТАРНОГО ВЗАИМОДЕЙСТВИЯ







We show that astrocyte can induce spatial synchronization in neuronal circuits defined by the morphological territory of the astrocyte. It is known that spatial synchronization in the brain is responsible for various cognitive functions (attention, recognition, navigation, making decisions, etc.) and for various pathologies (epileptic discharges, etc.).


frontiers in Physiology

ORIGINAL RESEARCH
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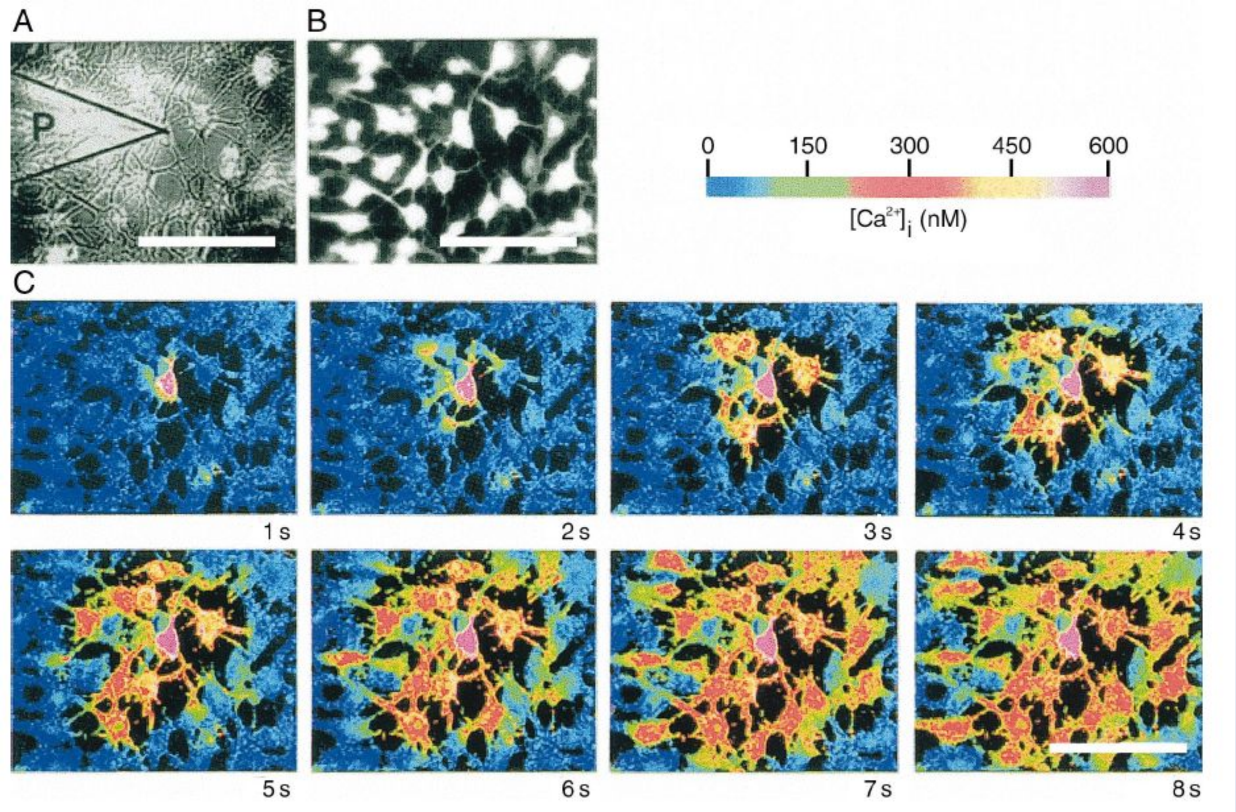
НЕЙМАРК

АСТРОЦИТАРНЫЕ СЕТИ

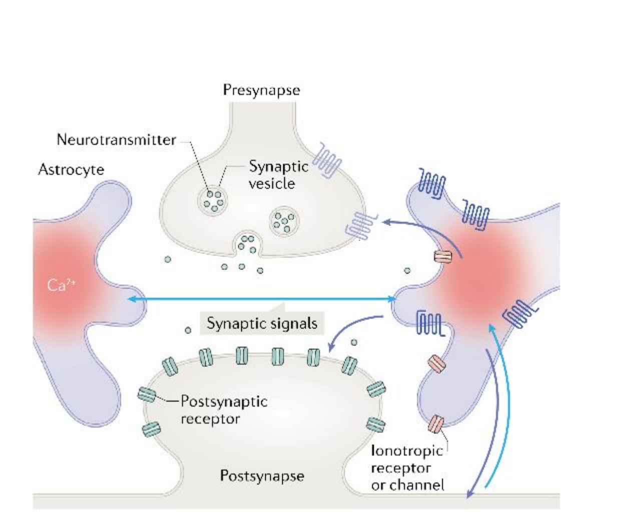
Astrocytes organize in complex networks through connections by gap junction channels. Calcium signals generated in individual cells, can propagate across these networks in the form of intercellular calcium waves, mediated by diffusion of second messengers molecules such as IP3.



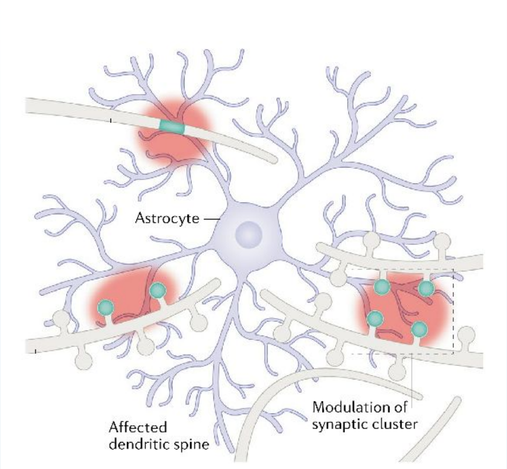
Araque et al., 2014

НЕЙРОН-АСТРОЦИТАРНЫЕ СЕТИ

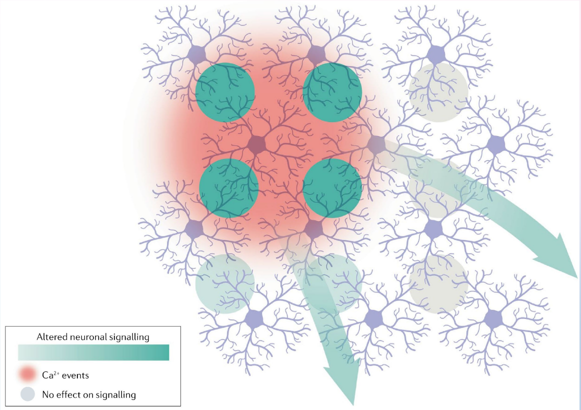
УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ



Астроцитарная регуляция передачи сигнала в одном синапсе



Гетеросинаптическая астроцитарная модуляция передачи сигнала

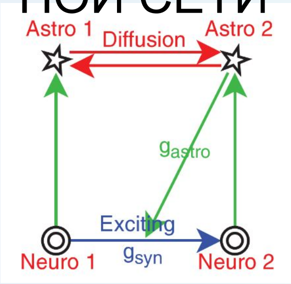


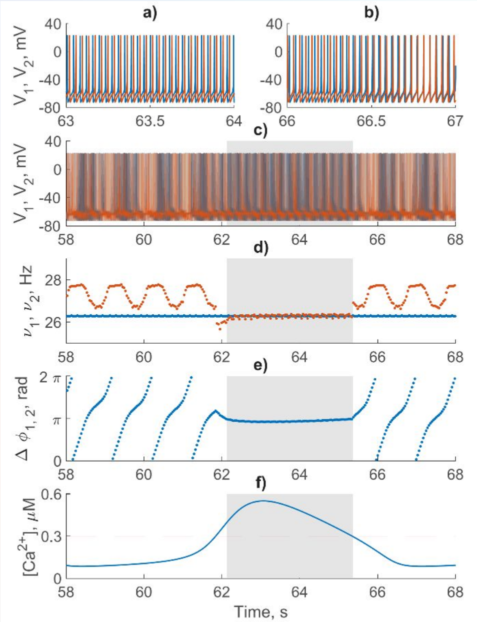
Нейрон-астроцитарное взаимодействие на сетевом уровне

Semyanov et al., Nat. Rev. Neurosci. 2020

НЕЙМАРК

МИНИМАЛЬНАЯ МОДЕЛЬ НЕЙРОН-АСТРОЦИТАРНОЙ СЕТИ





Neuron model (Hodgkin&Huxley, 1952)

$$C\frac{dV^{(i)}}{dt} = I_{channel}^{(i)} + I_{app}^{(i)} + \sum_j I_{syn}^{(ij)} + I_P^{(i)},$$

Synaptic current

$$I_{syn}^{(ij)} = \frac{g_{syneff}^{ij}(V^j - E_{syn})}{1 + \exp\left(\frac{-(V^i(t))}{k_{syn}}\right)},$$

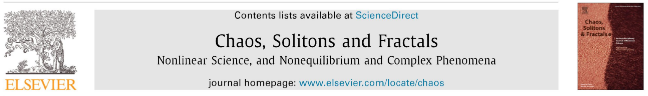
Calcium dynamics (Ullah et al., 2006)

$$\frac{d[Ca_c]^{(m)}}{dt} = J_{IP3R}{}^{(m)} - J_{SERCA}{}^{(m)} + J_{ERleak}{}^{(m)} + J_{in}{}^{(m)} - J_{out}{}^{(m)} + J_{diffCa}{}^{(m)},$$

$$\frac{d[IP_3]^{(m)}}{dt} = \frac{([IP_3]^* - [IP_3]^{(m)})}{\tau_r} + J_{PLC\delta}{}^{(m)} + J_{PLC\beta}{}^{(m)} + J_{diffIP3}{}^{(m)},$$

Astrocytic modulation of synaptic transmission

$$g_{syneff}{}^{ij} = \begin{cases} g_{syn}(1 + g_{astro}[Ca_c]^{(m)}), & if\ [Ca_c]^{(m)} > 0.3\ \mu M \\ g_{syn}, & otherwise \end{cases}$$

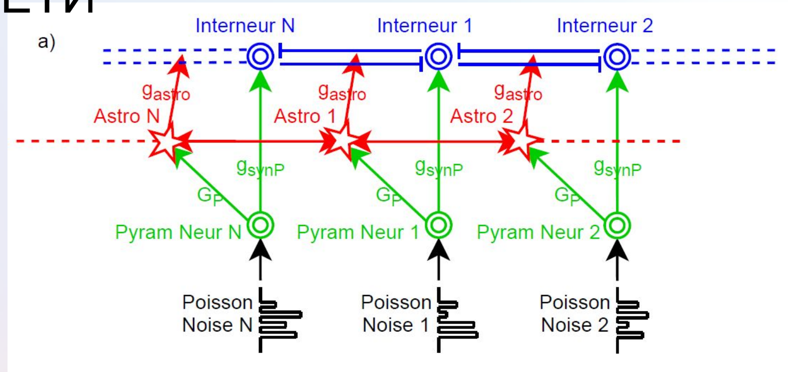

Contents lists available at ScienceDirect
Chaos, Solitons and Fractals
Nonlinear Science, and Nonequilibrium and Complex Phenomena
journal homepage: www.elsevier.com/locate/chaos

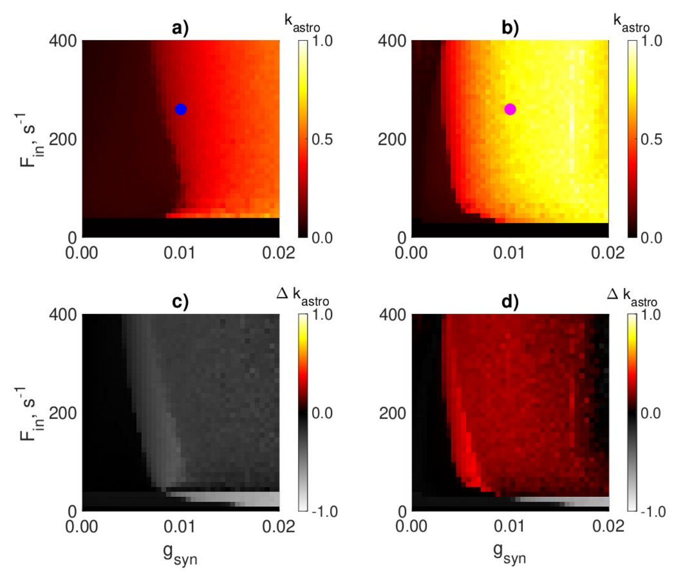
Astrocyte-induced intermittent synchronization of neurons in a minimal network

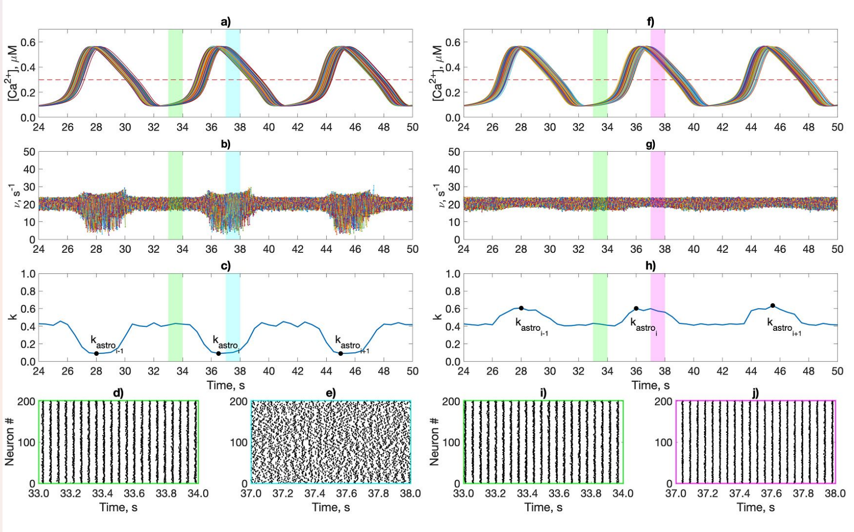
S Yu Makovkin[a,*], I V Shkerin[a], S Yu Gordleeva[a,b], M V Ivanchenko[a]

НЕЙМАРК

МОДЕЛЬ НЕЙРОН-АСТРОЦИТАРНОЙ СЕТИ







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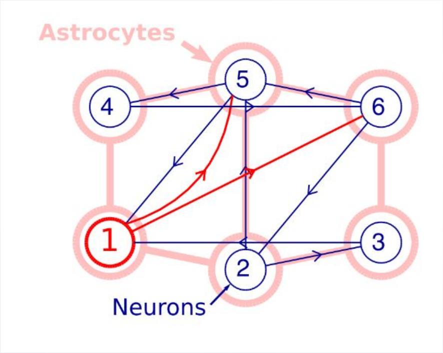
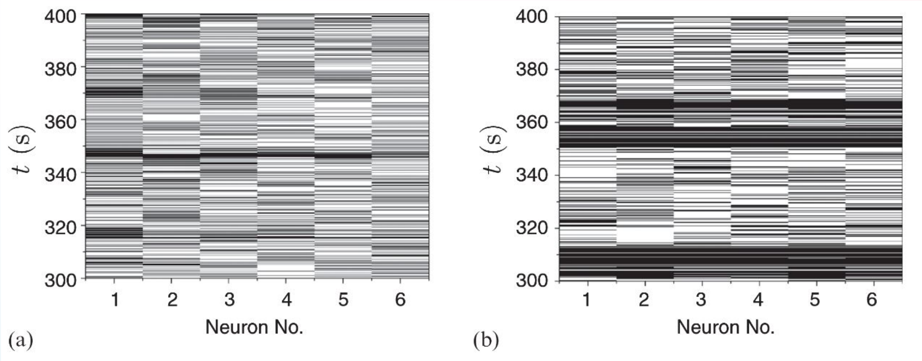
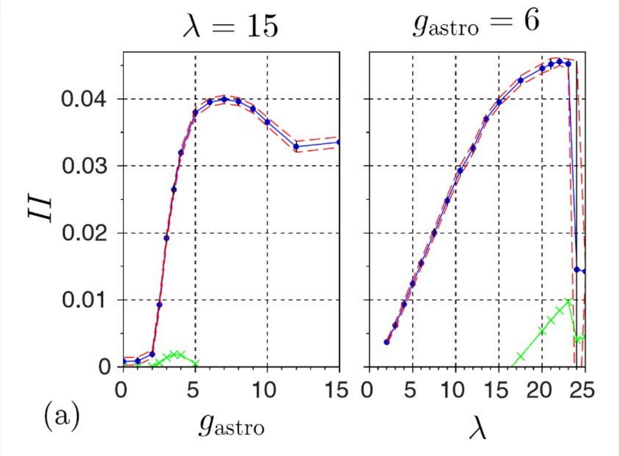
ИНФОРМАЦИЯ В МОДЕЛЯХ НЕЙРОН-АСТРОЦИТАРНЫХ СЕТЕЙ







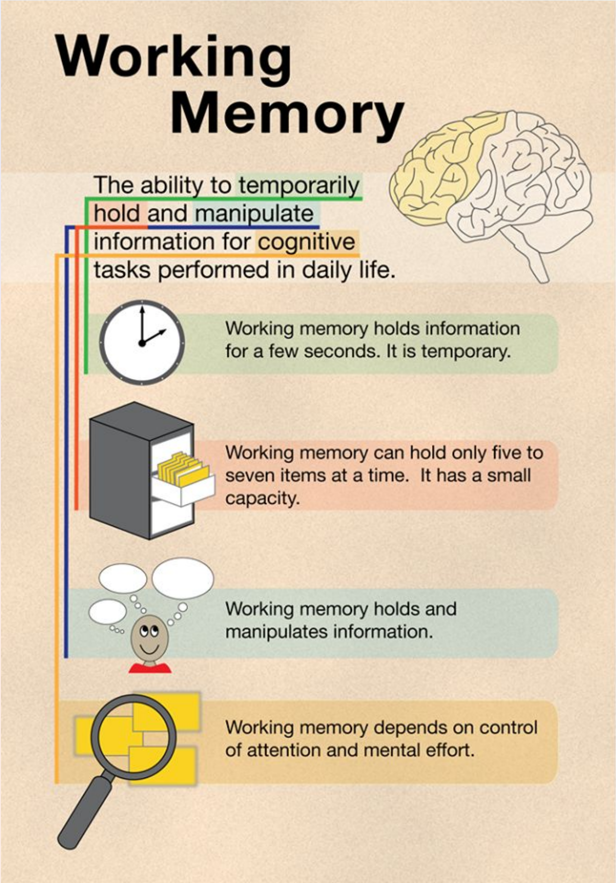
Integrated information (Barrett&Seth, 2011)

$$I_{\text{eff}}(AB) = I(x,y) - I(x_A, y_A) - I(x_B, y_B).$$

Mutual information

$$I(x,y) = H(x) + H(y) - H(xy)$$

$$H(x) = -\sum_x p_x \log_2 p_x$$

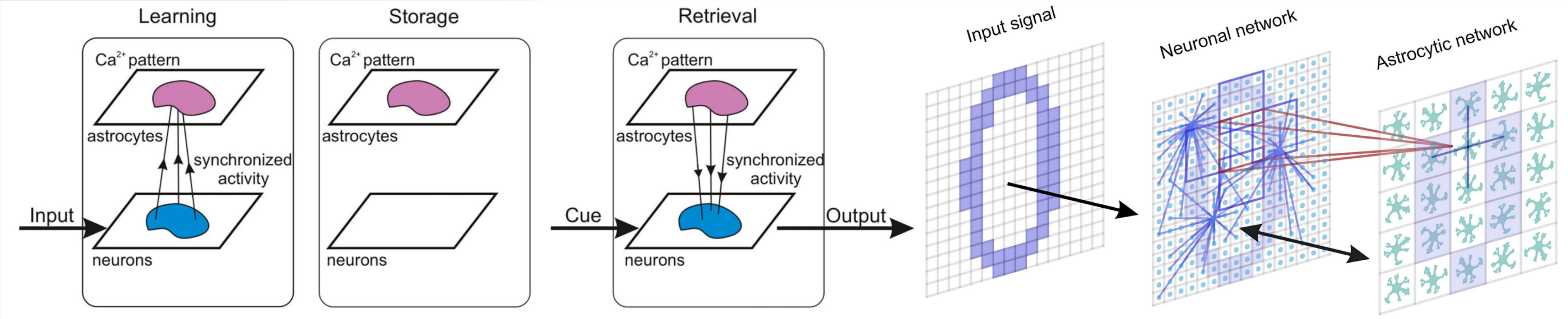


Why does the brain have astrocytic modulation of neuronal signaling?
What is the purpose of this modulation in terms of information processing and storage?

The coincidence of the characteristic times of calcium dynamics and astrocytic modulation of synaptic transmission with the times of short-term memory functioning.

Modeling Working Memory
in a Neuron-Astrocyte Network

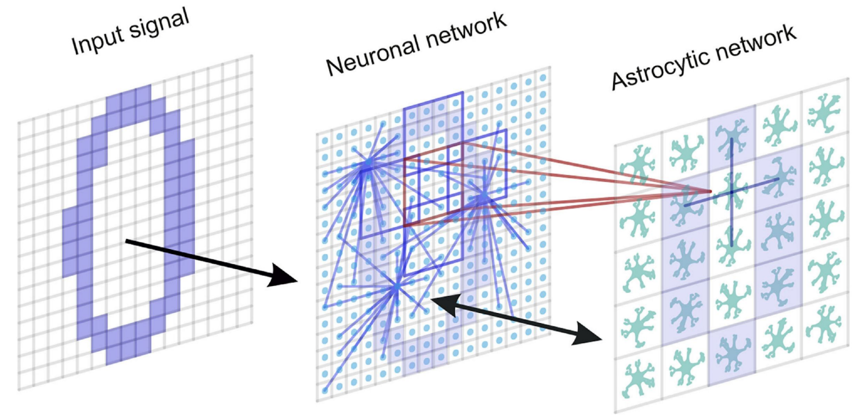
КОНЦЕПТ РАБОЧЕЙ ПАМЯТИ В СППАЙКОВОЙ МОДЕЛИ НЕЙРОН-АСТРОЦИТАРНОЙ СЕТИ

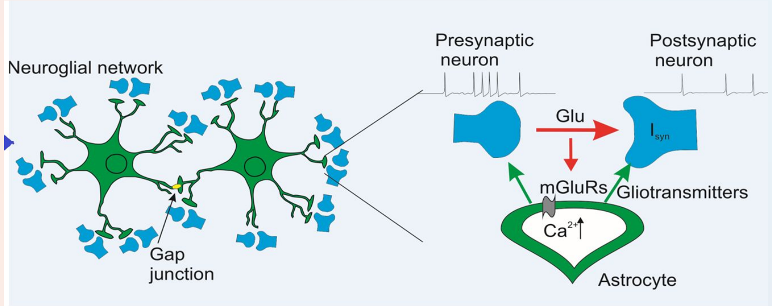


Considering the significance of WM processes and the challenge of finding alternative mechanisms and experimental evidence of the astrocytic role in information processing in CNS, it is interesting to study astrocyte-induced modulation of synaptic transmission in WM organization.

НЕЙМАРК

АРХИТЕКТУРА МОДЕЛИ





Izhikevich model (Izhikevich, 2003)

$$\frac{dV^{(i,j)}}{dt} = 0.04V^{(i,j)(2)} + 5V^{(i,j)} - U^{(i,j)} + 140 + I_{app}^{(i,j)} + I_{syn}^{(i,j)};$$

$$\frac{dU^{(i,j)}}{dt} = a\left(bV^{(i,j)} - U^{(i,j)}\right)$$

Synaptic current

$$I_{syn}^{(i,j)} = \sum_{k=1}^{N_{in}^{(i,j)}} \frac{g_{syn}^{(i,j)}\left(E_{syn} - V^{(i,j)}\right)}{1 + \exp\left(\frac{V_{pre}^{k}}{k_{syn}}\right)}$$

Calcium dynamics in astrocyte (Ullah et al., 2006):

$$\frac{d[Ca^{2+}]^{(m,n)}}{dt} = J_{\mathrm{ER}}^{(m,n)} - J_{\mathrm{pump}}^{(m,n)} + J_{\mathrm{leak}}^{(m,n)} + J_{\mathrm{in}}^{(m,n)} - J_{\mathrm{out}}^{(m,n)} + \mathrm{diff}_{Ca}^{(m,n)};$$

$$\frac{dh^{(m,n)}}{dt} = a_2\left(d_2\frac{IP_3^{(m,n)} + d_1}{IP_3^{(m,n)} + d_3}(1 - h^{m,n}) - [Ca^{2+}]^{(m,n)}h^{(m,n)}\right);$$

$$\frac{dIP_3^{(m,n)}}{dt} = \frac{IP_3^{*} - IP_3^{(m,n)}}{\tau_{IP3}} + J_{\mathrm{PLC}\delta}^{(m,n)} + J_{\mathrm{glu}}^{(m,n)} + \mathrm{diff}_{IP3}^{(m,n)},$$

Astrocyte-induced modulation of the synaptic weight

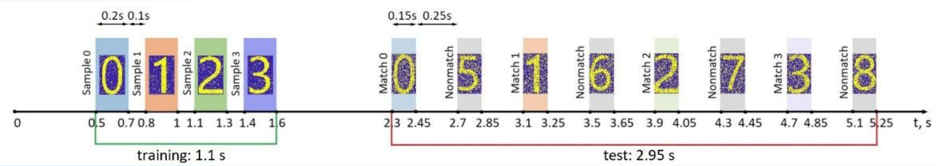
$$g_{syn}^{(i,j)} = \eta + \nu_{Ca}^{(m,n)}$$

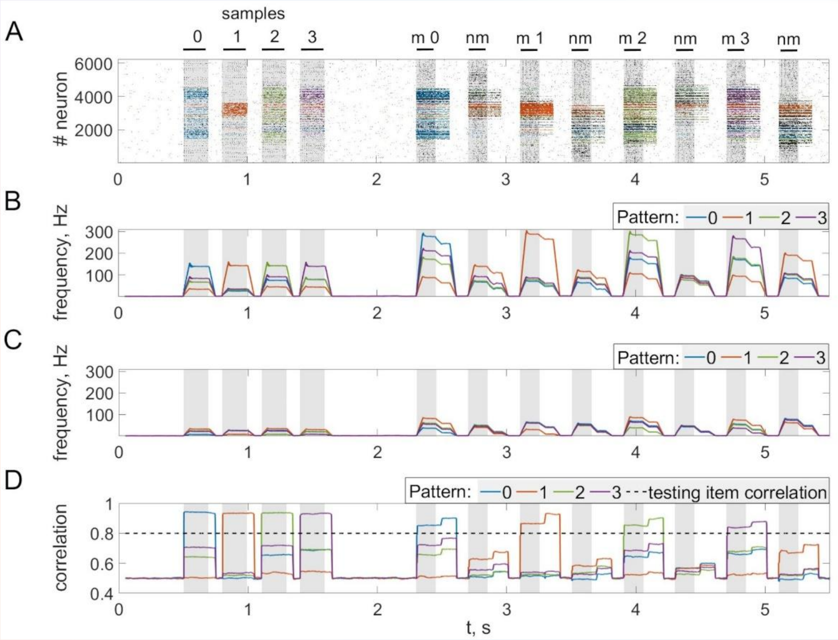
$$\nu_{Ca} = \nu_{Ca}^{*}\Theta\left(\left([Ca^{2+}]\right)^{(m,n)} - [Ca^{2+}]_{thr}\right)$$

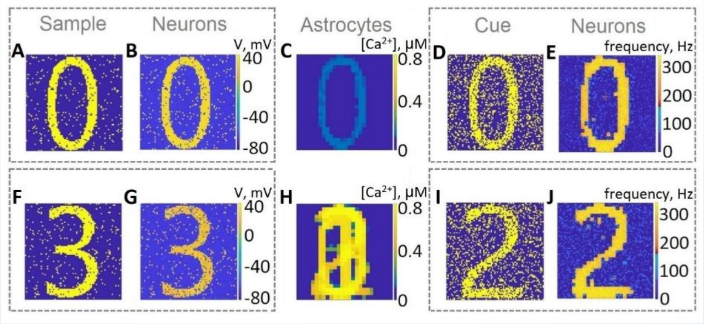
Multi-item Working Memory

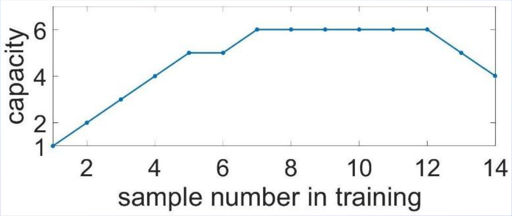
УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

Training and testing protocol





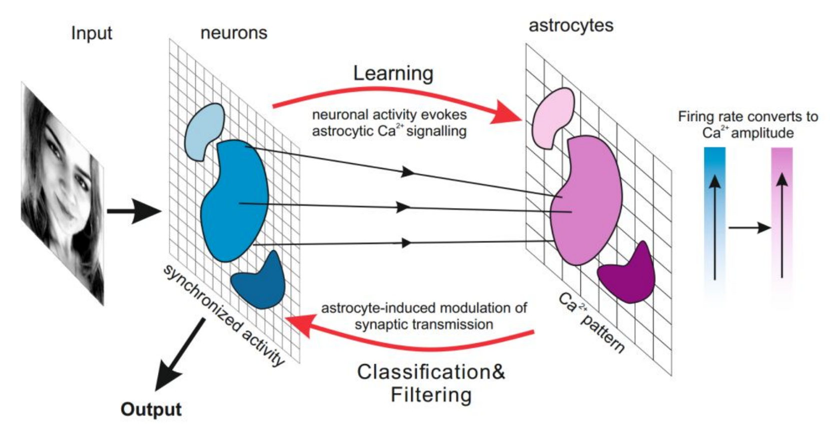


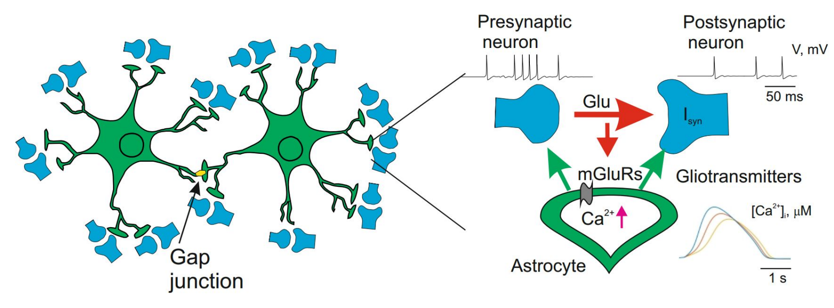


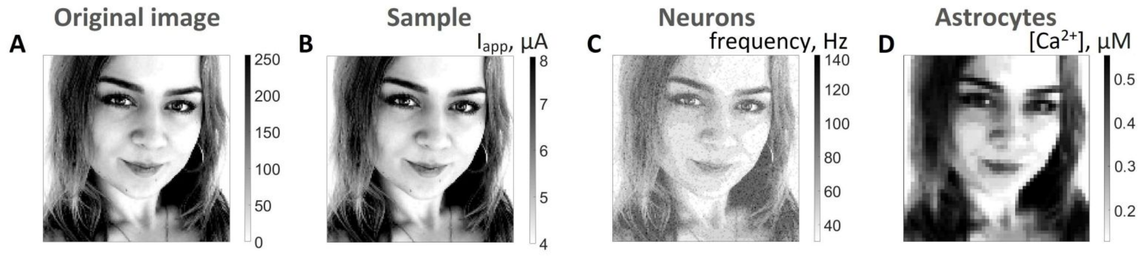
Gordleeva et al., Front. Cell. Neurosci.
doi: 10.3389/fncel.2021.631485

НЕЙМАРК

Analogous memory in a multi-layer neuron-astrocytic network







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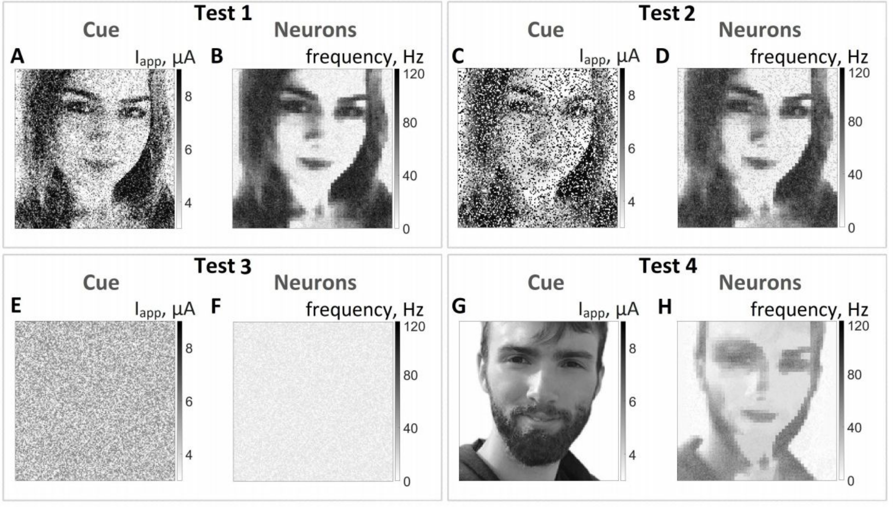
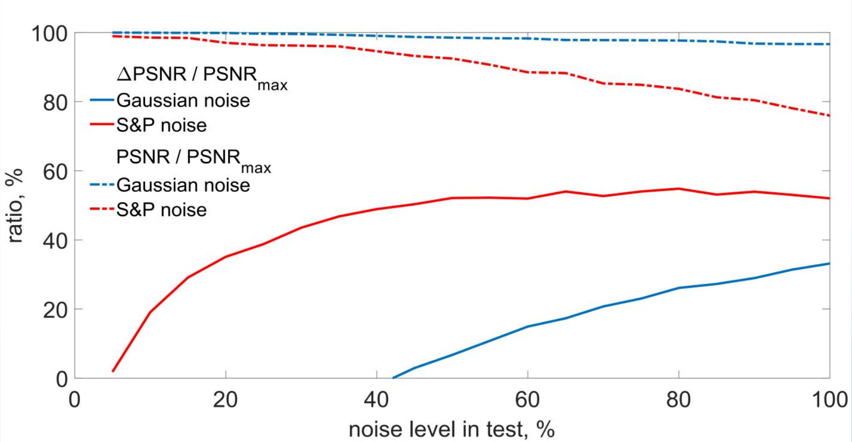




The system can robustly retrieve the memorized image even for a high noise level.

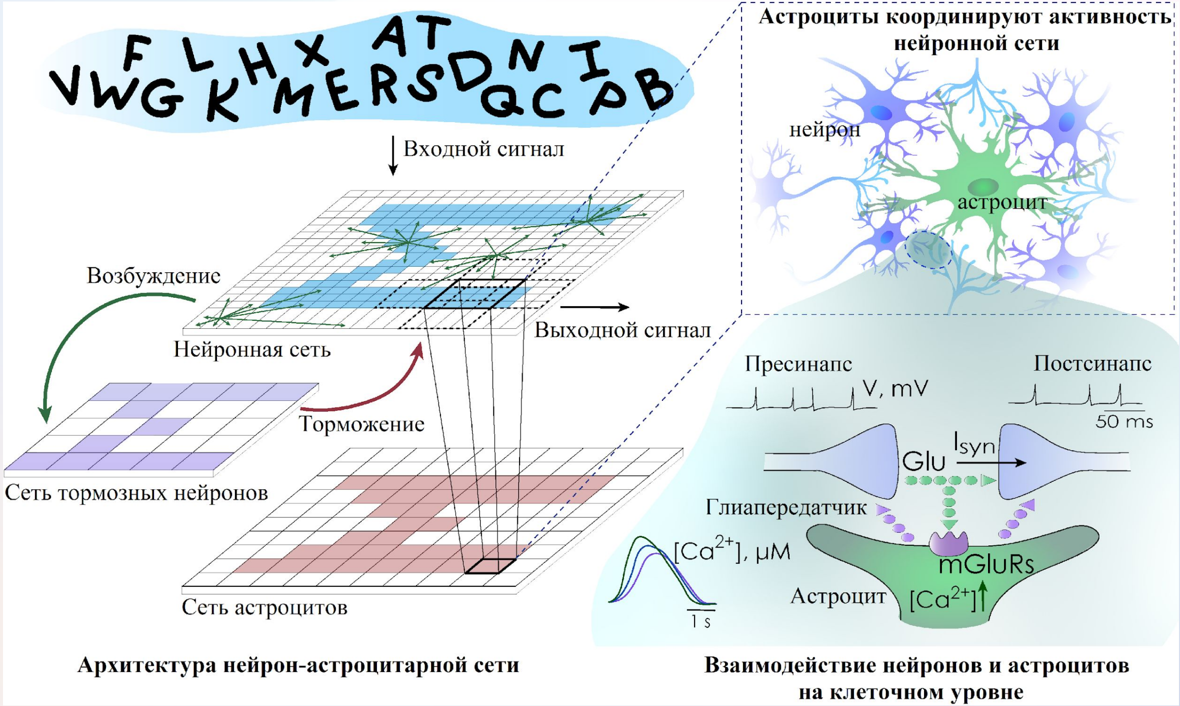
The model significantly improved the PSNR for pulse noise for all values within its level and for Gaussian noise for large values of its intensity.

УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО
НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

НЕЙМАРК

НЕЙРОМОРФНЫЙ ИИ НА НЕЙРОН-АСТРОЦИТАРНЫХ СЕТЯХ

Университет Лобачевского
Нижегородский государственный университет



Gordleeva et al., IEEE Trans Neural Netw Learn Syst
doi: 10.1109/TNNLS.2023.3335450

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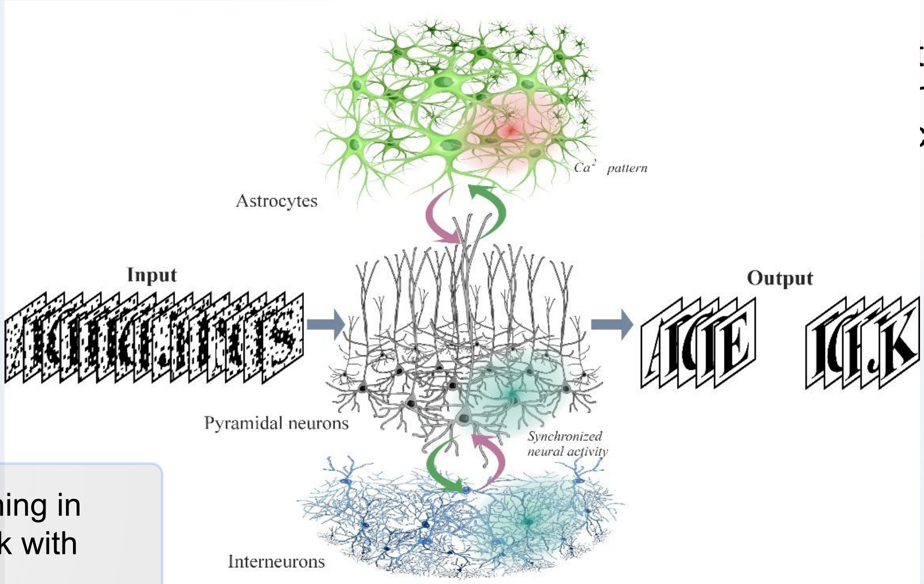
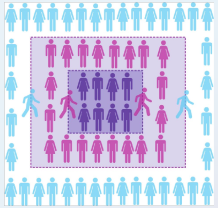


tuation-based memory
ne spiking
cyte network model

Situation-associated learning in Neuron-Astrocyte Network with STDP learning



A diagram of situation-based model of data

НЕЙМАРК

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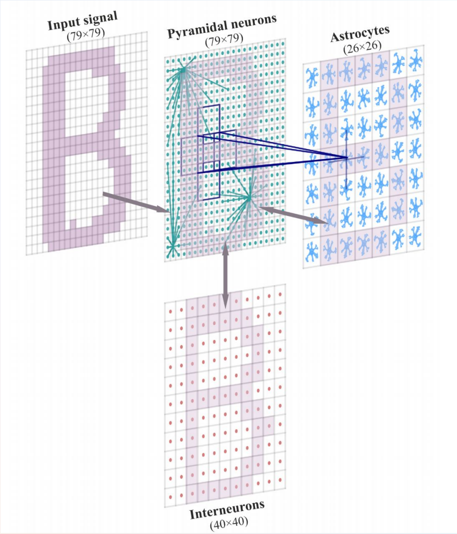

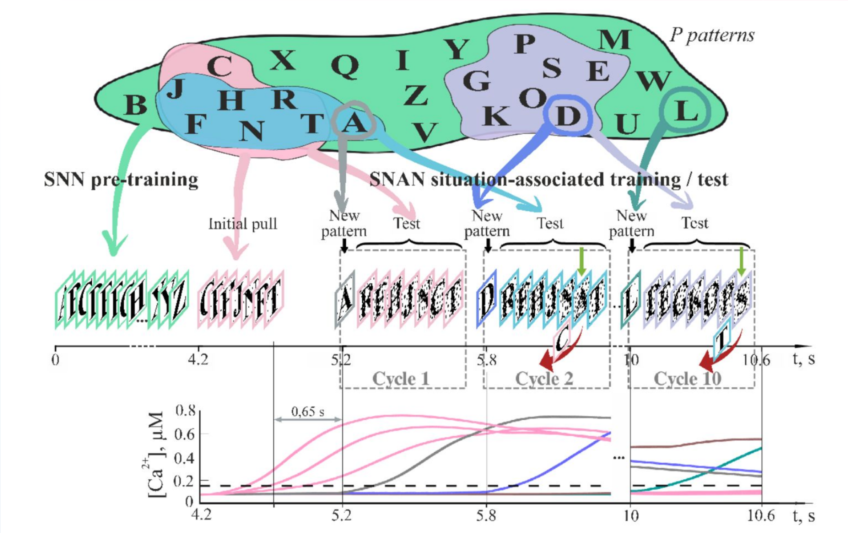

STDP learning rule

$$\delta w(\Delta t) = \begin{cases} A_0 exp(\frac{\Delta t}{\tau_+}), & \Delta t \le 0 \\ -A_0 exp(\frac{\Delta t}{\tau_-}), & \Delta t > 0 \end{cases}$$

Astrocytic modulation of synaptic transmission:

$$W^{(i,j)}_{gsyn\,E\to E} = \eta\,(1 + \nu_{Ca})$$

$$\nu_{Ca} = \nu^*_{Ca}\Theta([Ca^{2+}]^{(m,n)} - [Ca^{2+}]_{thr}), \eta = [0, gsyn_{EE}]$$

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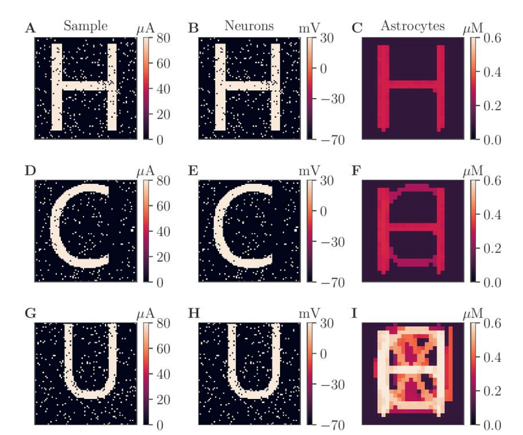
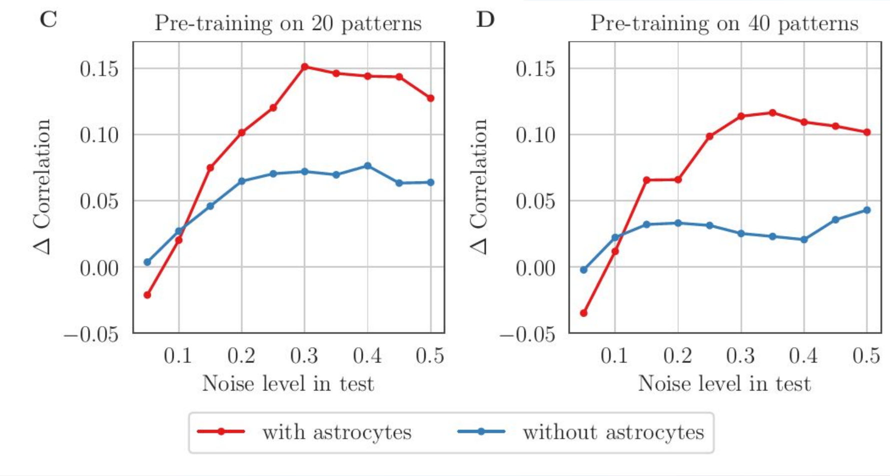




НЕЙМАРК

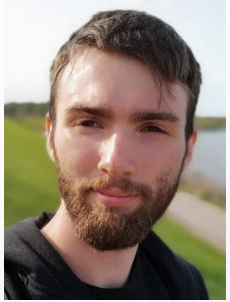
НАША КОМАНДА

Innokentiy Kastalskiy
Lobachevsky State University of Nizhny Novgorod,
Nizhny Novgorod, Russia

kastalskiy@neuro.nnov.ru

Yuliya Tsybina
Lobachevsky State University of Nizhny Novgorod,
Nizhny Novgorod, Russia

lotarevaj@gmail.com



Mikhail Krivonosov
Lobachevsky State University of Nizhny Novgorod,
Nizhny Novgorod, Russia

mike_live@mail.ru

Victor Kazantsev
Head of Neurotechnology Department,
Lobachevsky State University of Nizhny Novgorod, Russia

Innopolis University, Russia

kazantsev@neuro.nnov.ru

Alexey Zaikin
Lobachevsky State University of Nizhny Novgorod,
Nizhny Novgorod, Russia

Sechenov First Moscow State Medical University,
Moscow, Russia

University College London, London, UK

alexey.zaikin@ucl.ac.uk

Alexander Gorban
Lobachevsky State University of Nizhny Novgorod,
Nizhny Novgorod, Russia

University of Leicester,
Leicester, UK

a.n.gorban@leicester.ac.uk

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