

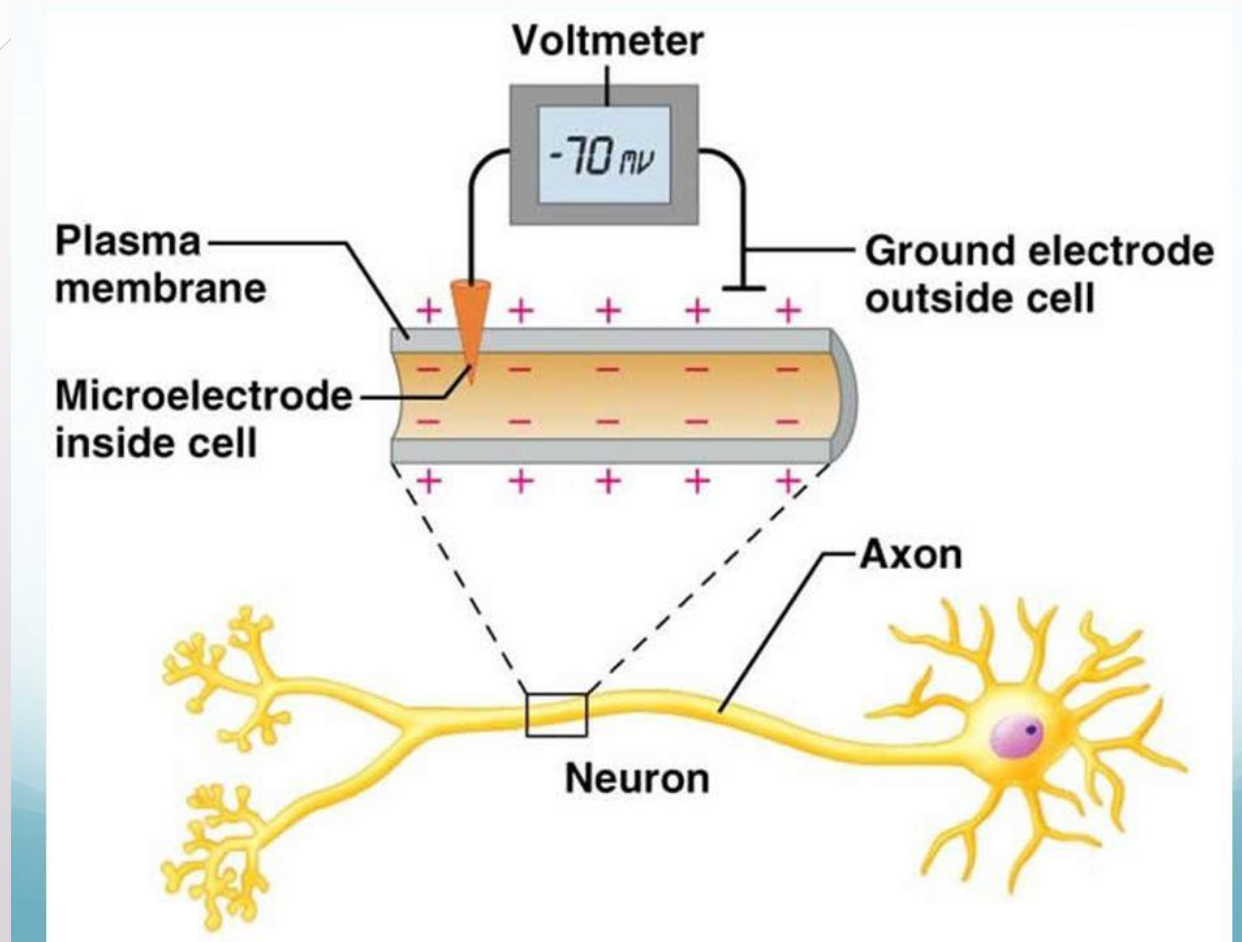
Моделиране на МОЗЪЧНАТА АКТИВНОСТ: МЕТОДИ И ПРИЛОЖЕНИЯ

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ИИКТ-БАН

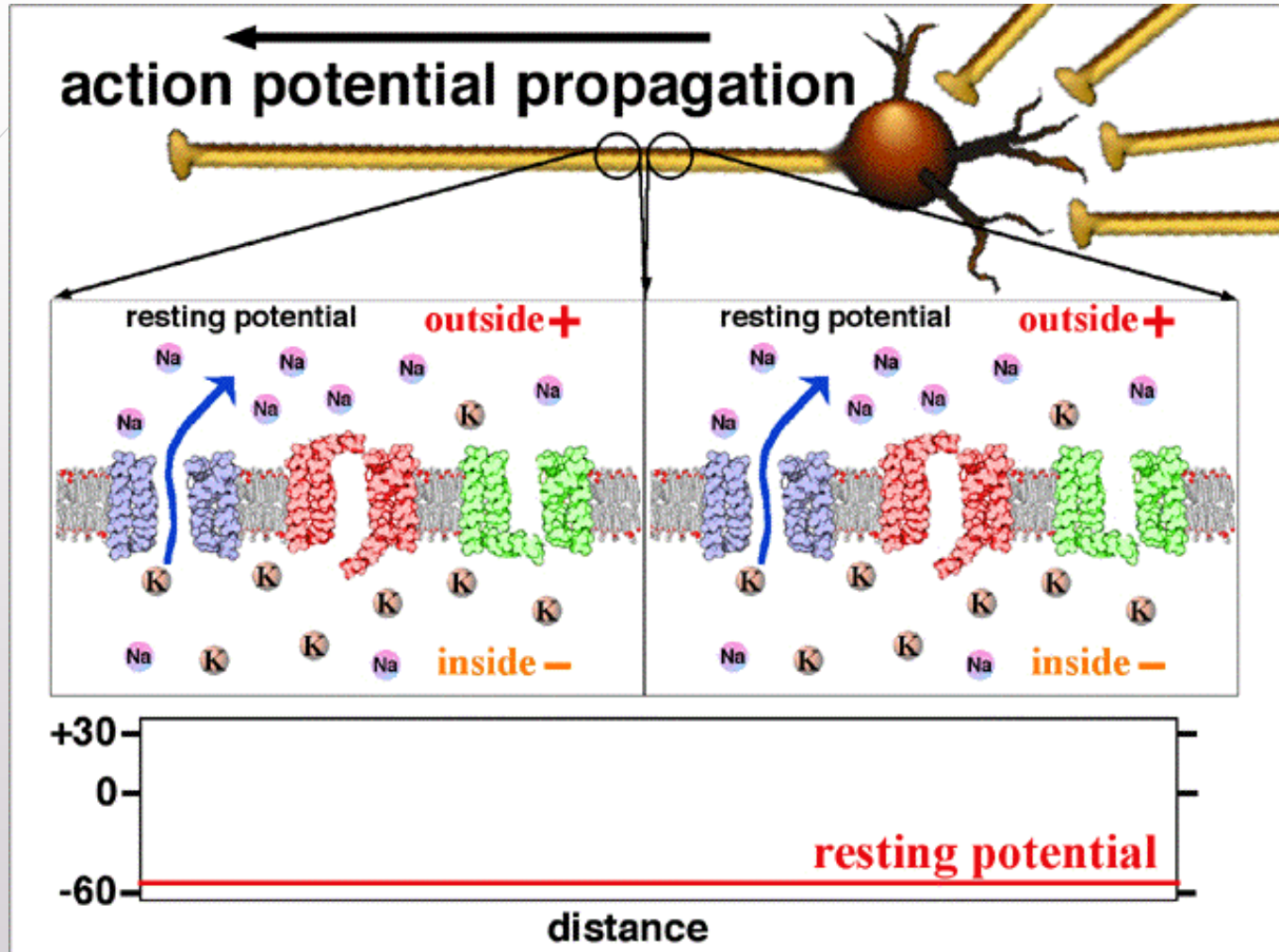
Съдържание на лекцията

1. Биологично обосновани модели на нервните клетки и на връзките между тях
2. NEST Simulator – библиотека за симулация на биологично обосновани модели на мозъчната активност
3. Типове данни, използвани за моделиране на мозъчната активност
4. Примери:
 - ▶ Модел на зрителната система
 - ▶ Модел на базалните ганглии и reinforcement обучение
 - ▶ Симулационно изследване на влиянието на възрастта върху връзките в мозъка
 - ▶ Симулационно изследване на ефекта от „повреди“ (лезии) в мозъка

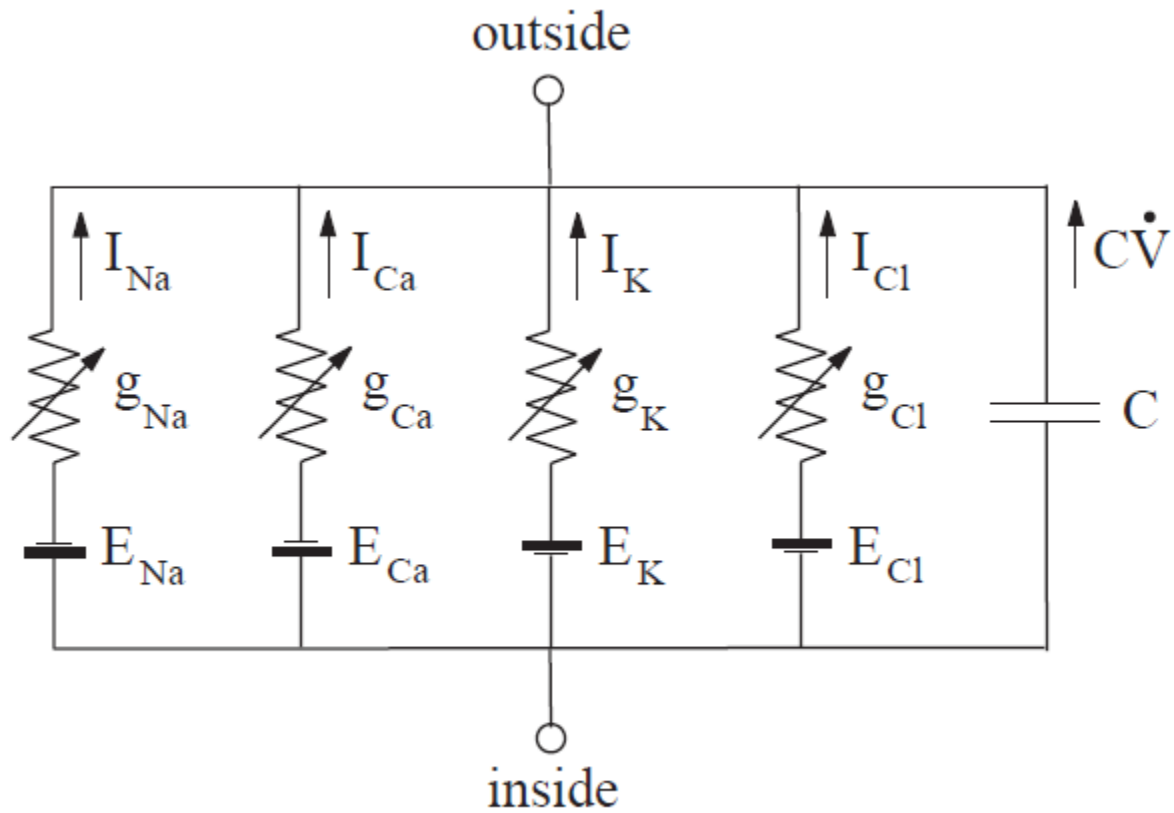
Моделиране на ниво неврон



Потенциал на клетъчната мембрана



Моделiranje на ниво невррон



$$I = C\dot{V} + I_{Na} + I_{Ca} + I_K + I_{Cl}$$

$$I_{Na} = g_{Na}(V - E_{Na})$$

$$I_{Ca} = g_{Ca}(V - E_{Ca})$$

$$I_K = g_K(V - E_K)$$

$$I_{Cl} = g_{Cl}(V - E_{Cl})$$

$$E_K < E_{Cl} < V_{rest} < E_{Na} < E_{Ca}$$

Уравнения на Hodgkin-Huxley

$$\begin{aligned} C \dot{V} &= I - \overbrace{\bar{g}_K n^4 (V - E_K)}^{I_K} - \overbrace{\bar{g}_{Na} m^3 h (V - E_{Na})}^{I_{Na}} - \overbrace{g_L (V - E_L)}^{I_L} \\ \dot{n} &= \alpha_n(V)(1 - n) - \beta_n(V)n \\ \dot{m} &= \alpha_m(V)(1 - m) - \beta_m(V)m \\ \dot{h} &= \alpha_h(V)(1 - h) - \beta_h(V)h, \end{aligned}$$

Cl⁻

$$E_K = -12 \text{ mV} \quad E_{Na} = 120 \text{ mV}, \quad E_L = 10.6 \text{ mV};$$

$$\bar{g}_K = 36 \text{ mS/cm}^2 \quad \bar{g}_{Na} = 120 \text{ mS/cm}^2, \quad g_L = 0.3 \text{ mS/cm}^2.$$

$$\alpha_n(V) = 0.01 \frac{10 - V}{\exp(\frac{10 - V}{10}) - 1}$$

$$\beta_n(V) = 0.125 \exp\left(\frac{-V}{80}\right)$$

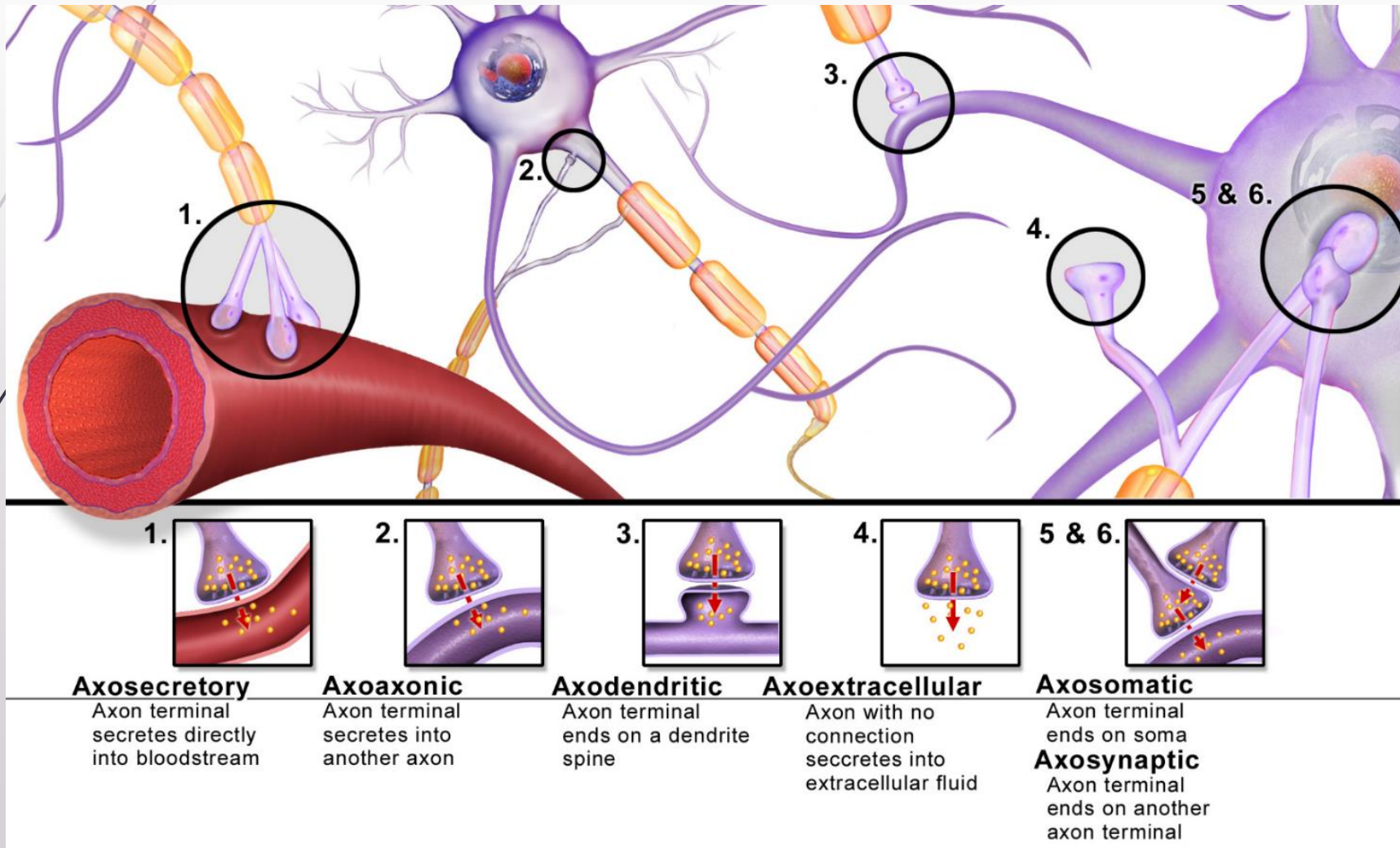
$$\alpha_m(V) = 0.1 \frac{25 - V}{\exp(\frac{25 - V}{10}) - 1}$$

$$\beta_m(V) = 4 \exp\left(\frac{-V}{18}\right)$$

$$\alpha_h(V) = 0.07 \exp\left(\frac{-V}{20}\right)$$

$$\beta_h(V) = \frac{1}{\exp(\frac{30 - V}{10}) + 1}.$$

Типове синапси



Модели на синапси, основани на проводимост

$$I_{syn} = \sum_k g_k(t)(V - V_k)$$

$$g_k(t) = \bar{g}_k \sum_n \alpha(t - t_n) \quad \alpha(t) = \frac{a_r a_d}{a_r - a_d} \left(e^{-a_d t} - e^{-a_r t} \right)$$

$$g_k(t) = \bar{g}_k \alpha(t) \quad \alpha(t) = \sum_n e^{-(t-t_n)/\tau} H(t-t_n)$$
$$\alpha(t) = \sum_n \left(1 - e^{-(t-t_n)/\tau_r} \right) \left(a e^{-(t-t_n)/\tau_f} + (1-a) e^{-(t-t_n)/\tau_s} \right) H(t-t_n)$$

$$g_k(t) = \bar{g}_k s(t) \quad \frac{ds}{dt} = a_r [T](1-s) - a_d s$$

Модели на синапси с пост-синаптичен ток

$$I_{syn}(i) = \sum_j A_{ij} y_{ij}(t)$$

$$\frac{dy}{dt} = -\frac{y}{\tau_1} + ux\delta(t - t_{sp})$$

$$\frac{dx}{dt} = -\frac{x}{\tau_{rec}} - ux\delta(t - t_{sp})$$

$$\frac{dz}{dt} = \frac{y}{\tau_1} - \frac{z}{\tau_{rec}}$$

$$\frac{du}{dt} = -\frac{u}{\tau_{facil}} + U(1 - u)\delta(t - t_{sp})$$

Адаптация задвижвана от събитие

$$\Delta w = \begin{cases} -\lambda f_-(w) \times K(\Delta t), & \Delta t \leq 0 \\ \lambda f_+(w) \times K(\Delta t), & \Delta t > 0 \end{cases}$$

$$\Delta t = t_{post} - t_{pre}$$

$$K(\Delta t) = e^{-|\Delta t|/\tau}$$

$$0 \leq \lambda \ll 1$$

$$f_+(w) = (1 - w)^\mu$$

$$f_-(w) = \alpha w^\mu$$

АДАПТАЦИЯ ЗАДВИЖВАНА ОТ НЕВРОМОДУЛАТОР

$$\dot{w} = c(n - b)$$

$$\dot{c} = -\frac{c}{\tau_c} + STDP(\Delta t)\delta(t - t_{pre/post})C_1$$

$$\dot{n} = -\frac{n}{\tau_n} + \frac{\delta(t - t_n)}{\tau_n}C_2$$

$$STDP(\Delta t) = \begin{cases} A_+ e^{-|\Delta t|/\tau_+}, & \Delta t > 0 \\ A_- e^{-|\Delta t|/\tau_-}, & \Delta t \leq 0 \end{cases}$$

$$\Delta t = t_{post} - t_{pre}$$

NEST Simulator - средство за моделиране на мозъка

Предоставя:

- ▶ Над 50 модела на неврони, описани в литературата
- ▶ Над 10 модела на синапси, включително пластични
- ▶ Възможност за дефиниране на големи структури от неврони и връзките между тях, включително от експериментални данни или теоретично дефинирани
- ▶ Възможност за наблюдение на симулацията на ниво неврон
- ▶ Работи на компютърни конфигурации от настолни и преносими до суперкомпютри

Приложения на NEST Simulator

Моделите предоставят възможност за неинвазивни изследвания на:

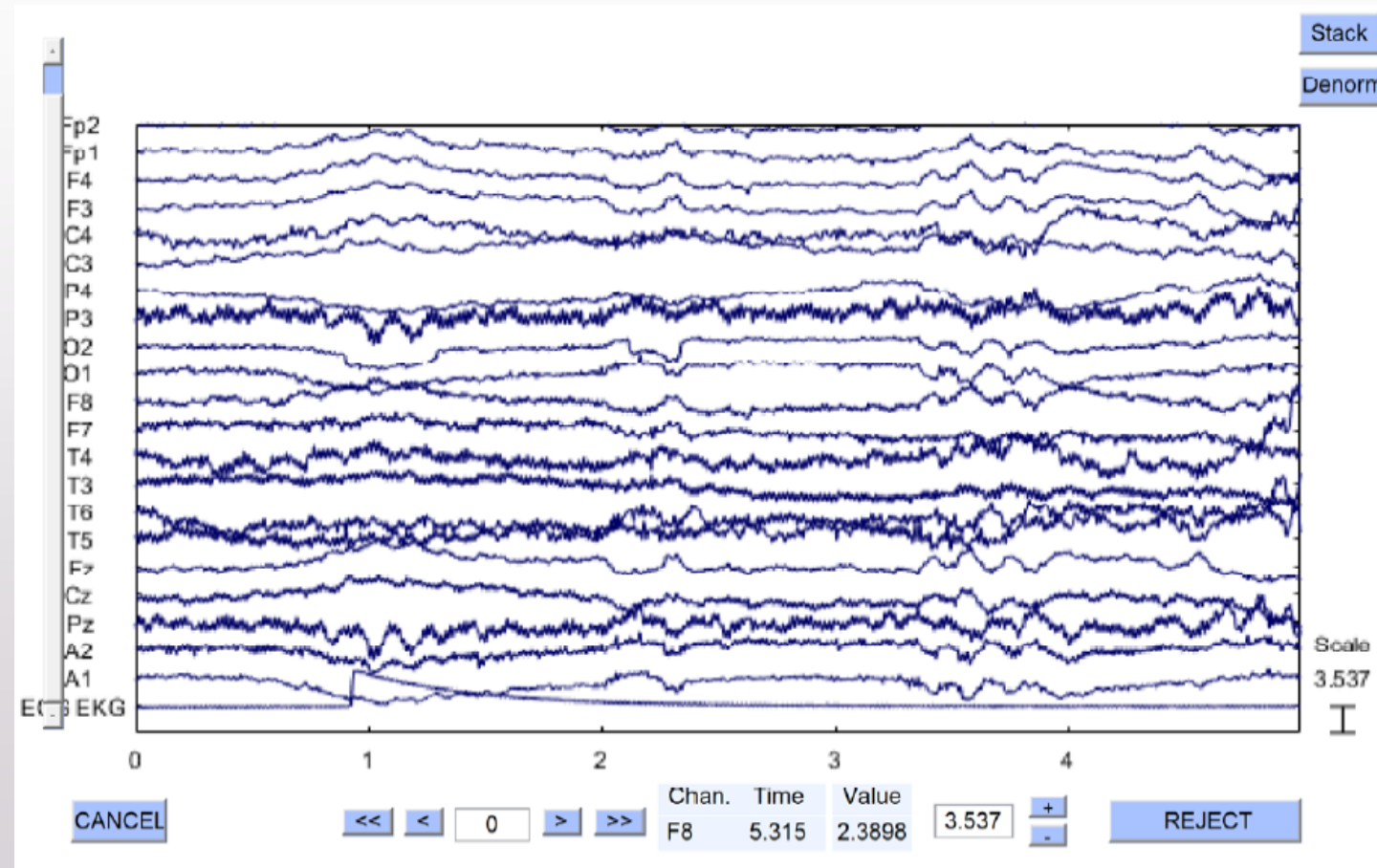
- ▶ Мозъчната активност при различни параметри на модела
- ▶ Влияние на структурните промени в мозъка (лезии или загуба на връзки)
- ▶ Влияние на възрастта върху параметрите на моделите (връзки между структурите в мозъка)

Типове данни, използвани за моделиране на мозъчната активност

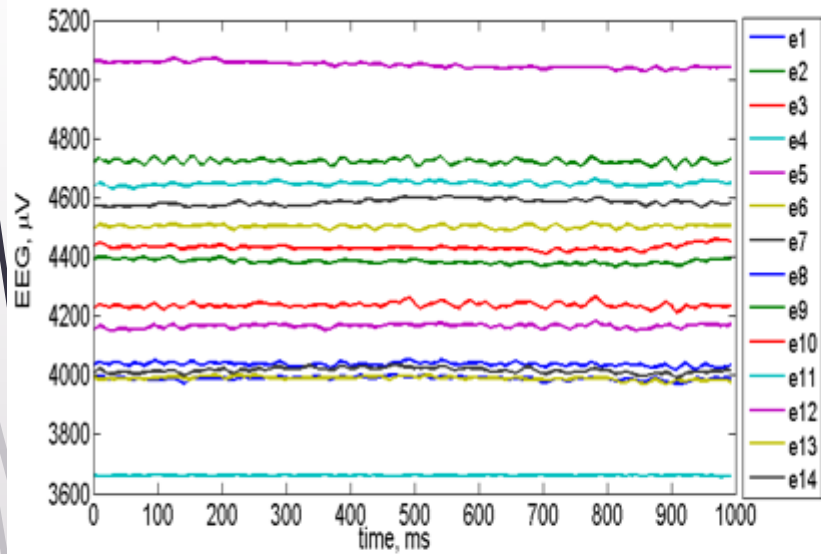
- ▶ Измервания с дълбоки електроди – дават информация само за конкретна област от мозъка
- ▶ EEG записи – дават информация за активността на мозъчната кора
- ▶ MRI (fMRI) изображения – дават информация за тримерната структура на мозъка
- ▶ Психо-физиологични експерименти – дават индиректна информация как мозъкът обработва външните стимули (изображения, мирис, звук, допир и др.п.)

EEG измервания на мозъчната активност

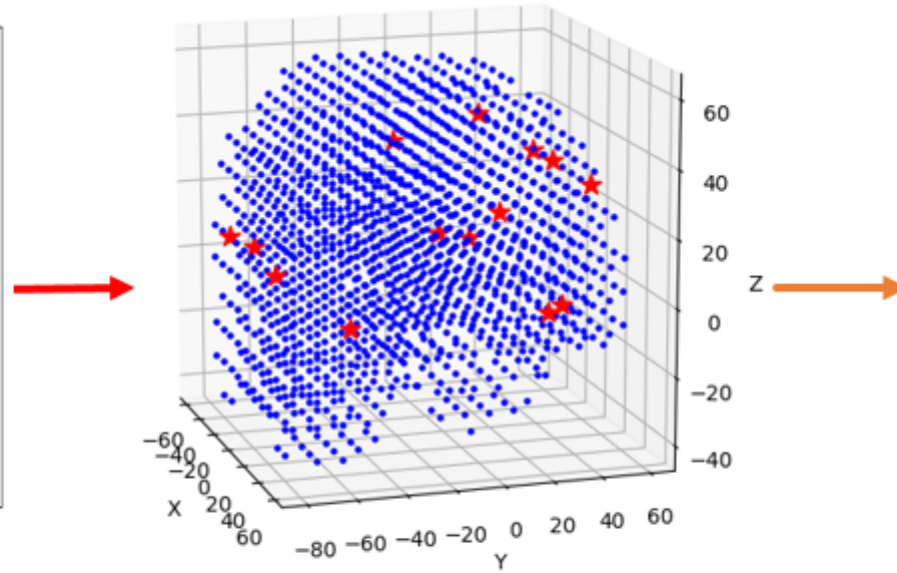
EEG сензорите измерват пост-синаптичния потенциал, но само на мозъчната кора.



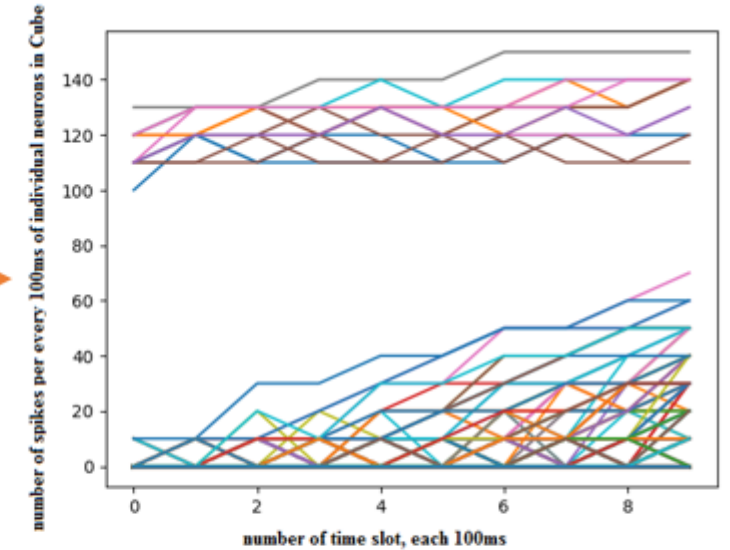
Пример за „обратно инженерство“ на активността на мозъка от EEG данни



EEG recordings



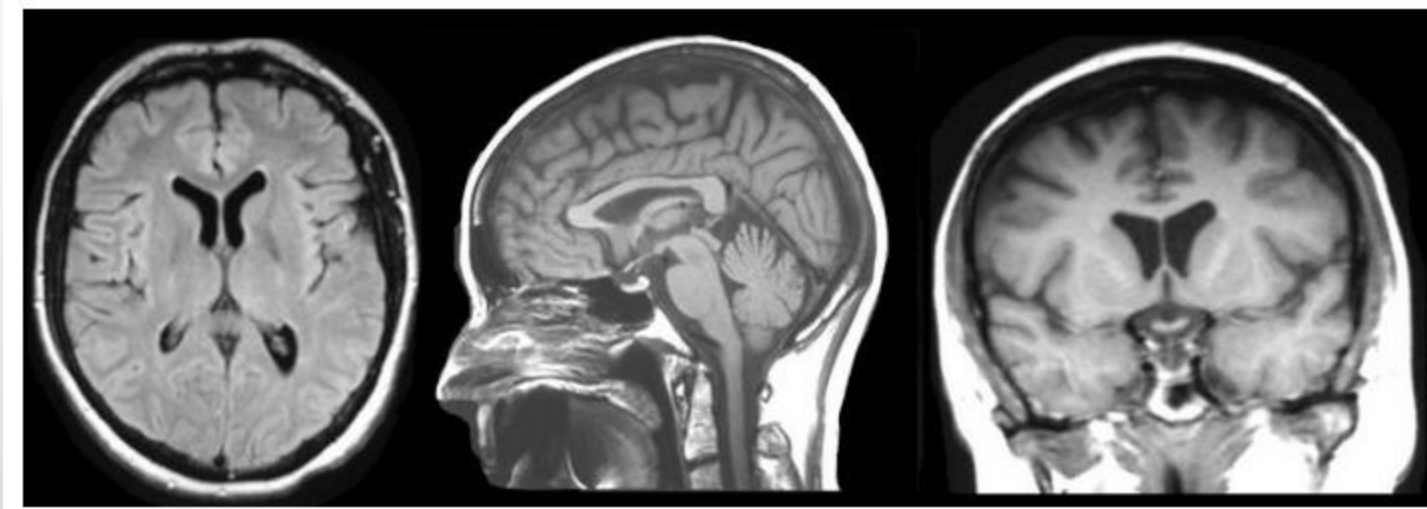
3D BrainCube of SNN with STDP plasticity



Cube firing rates

MRI (fMRI) данни

MRI предоставя детайлно изображение на мозъка. От тях може да бъде получена информация и за свързаността на областите в мозъка.



Пример 1: Извличане на информация за връзките в мозъчната кора от MRI

A Whole-Cortex Probabilistic Diffusion Tractography Connectome
 Burke Q. Rosen, Eric Halgren
 eNeuro 22 January 2021, 8 (1)
 ENEURO.0416-20.2020; DOI:
 10.1523/ENEURO.0416-20.2020

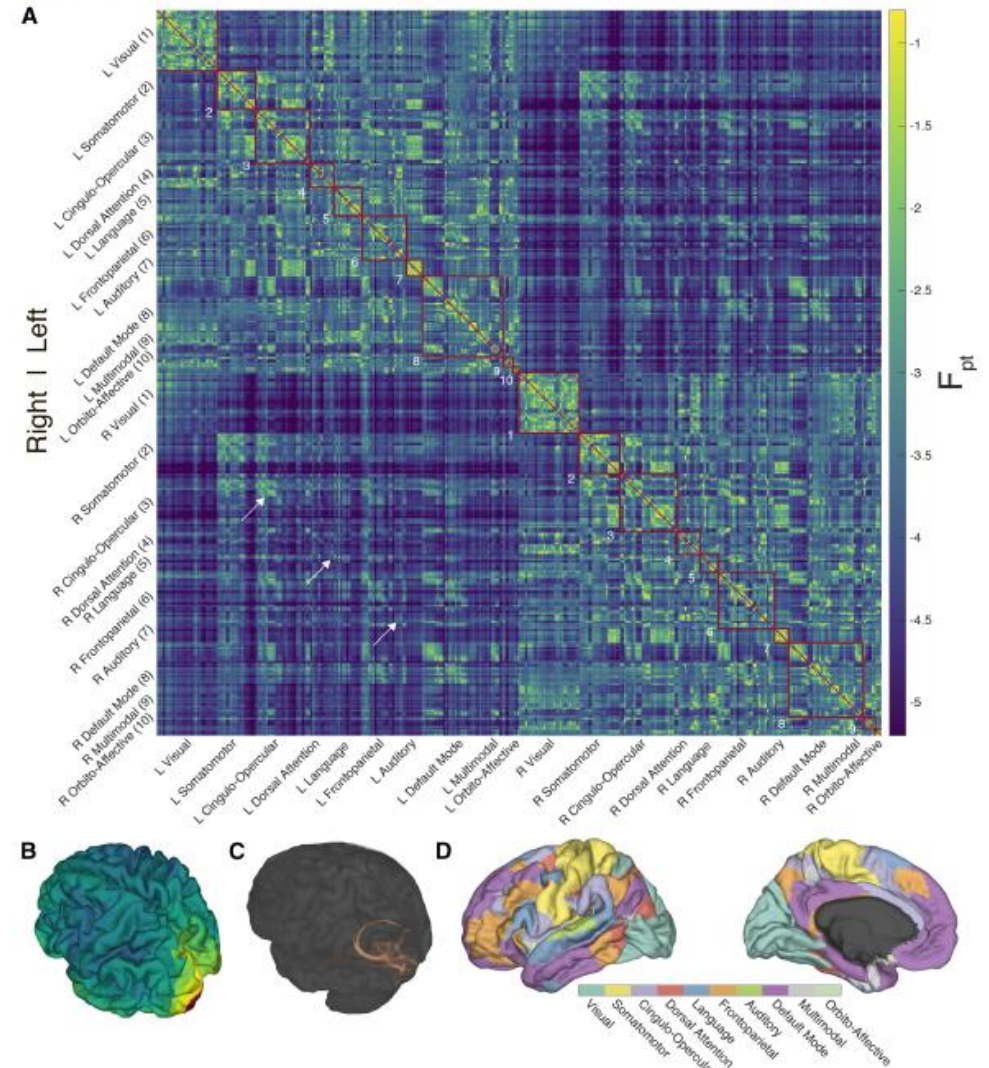


Figure 1. Probabilistic diffusion tractography structural connectome of the human cortex. **A**, Group average ($N = 1065$) structural connectivity matrix consisting of the 360 HCP-MMPS1.0 atlas parcels organized into 10 functional networks. Raw streamline counts are fractionally scaled yielding the log probability F_{pt} . The white arrows highlight the diagonal which contains contralateral homologs. **B**, The first row of the connectivity matrix, showing connection probabilities from left V1 to all other parcels, projected onto the fsaverage template cortex. **C**, Single subject (100307) volume ray casting visualization of left V1-originating streamline probabilities within the skull-stripped T1-weighted structural MR volume. **D**, Ten functional networks, adapted from Ji et al. (2019), within HCP-MMPS1.0 atlas. These are indicated by red boxes in panel **A**.

Пример 2: Извличане на информация за връзките в дълбочина в мозъка от MRI

Alemán-Gómez, Y., Griffa, A., Houde, JC. *et al.* A multi-scale probabilistic atlas of the human connectome. *Sci Data* **9**, 516 (2022).
<https://doi.org/10.1038/s41597-022-01624-8>

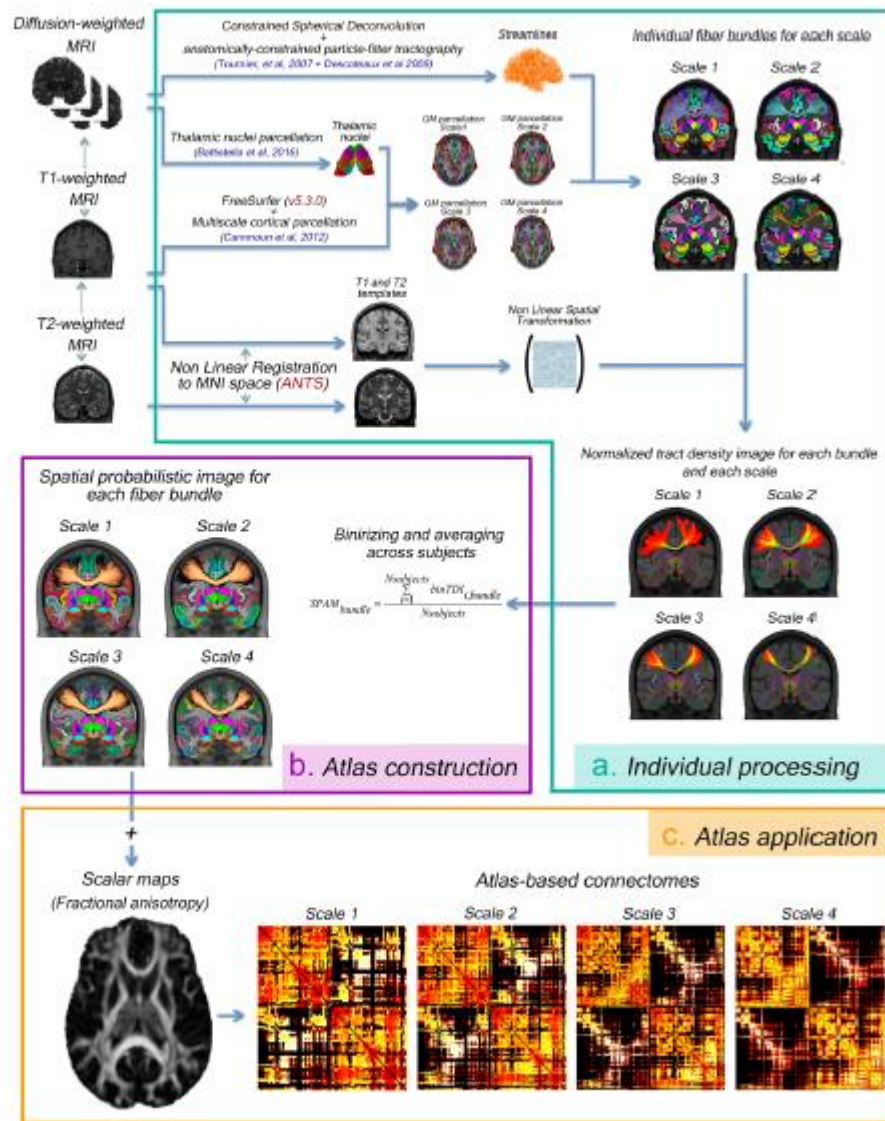
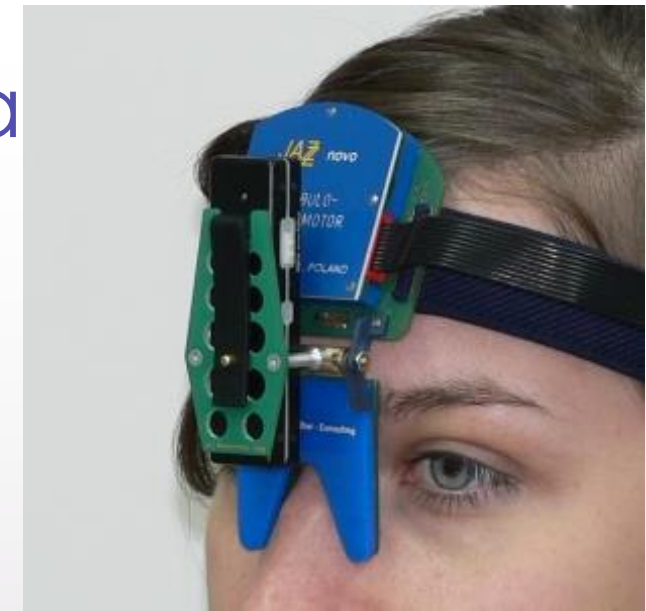
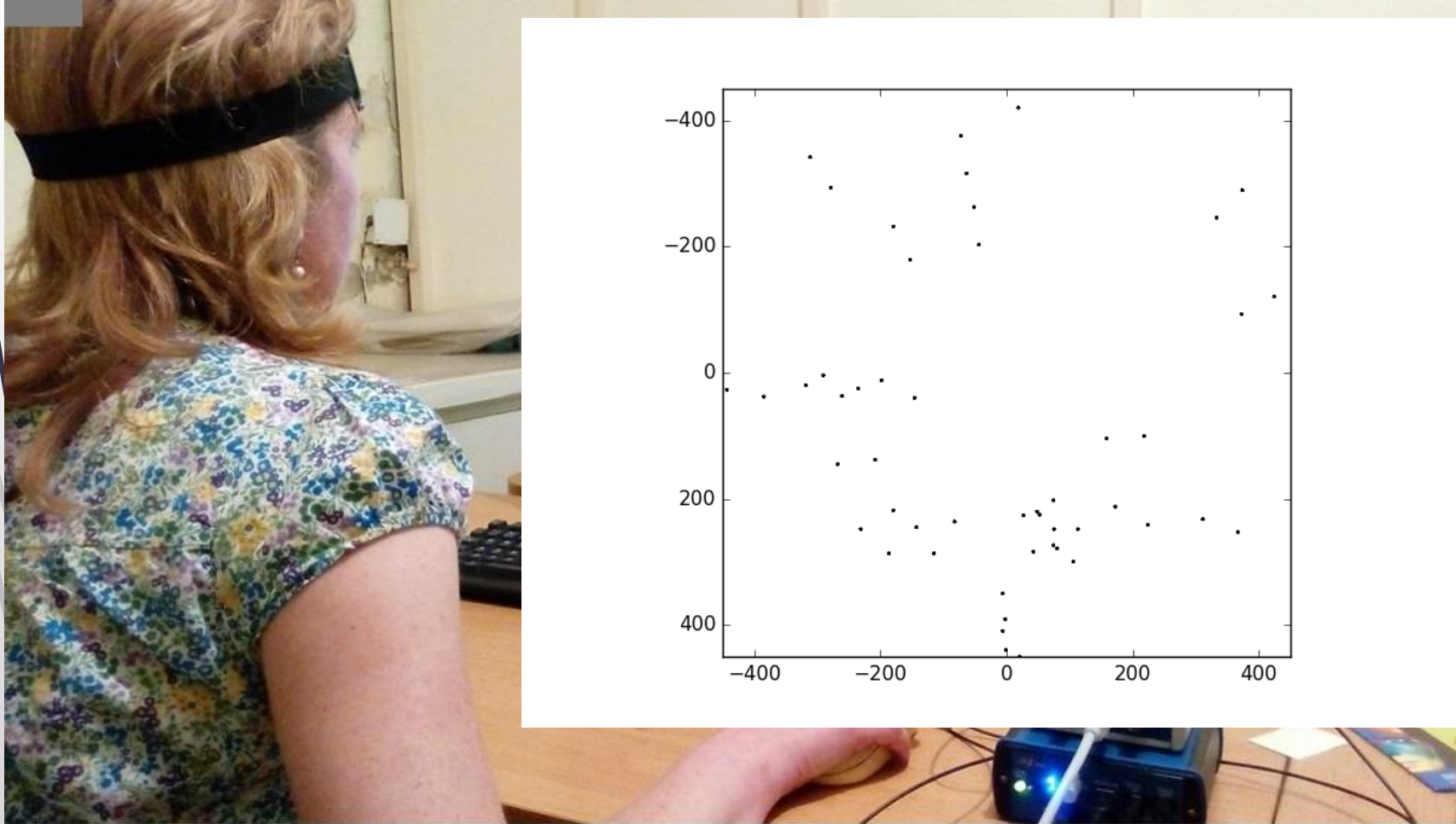


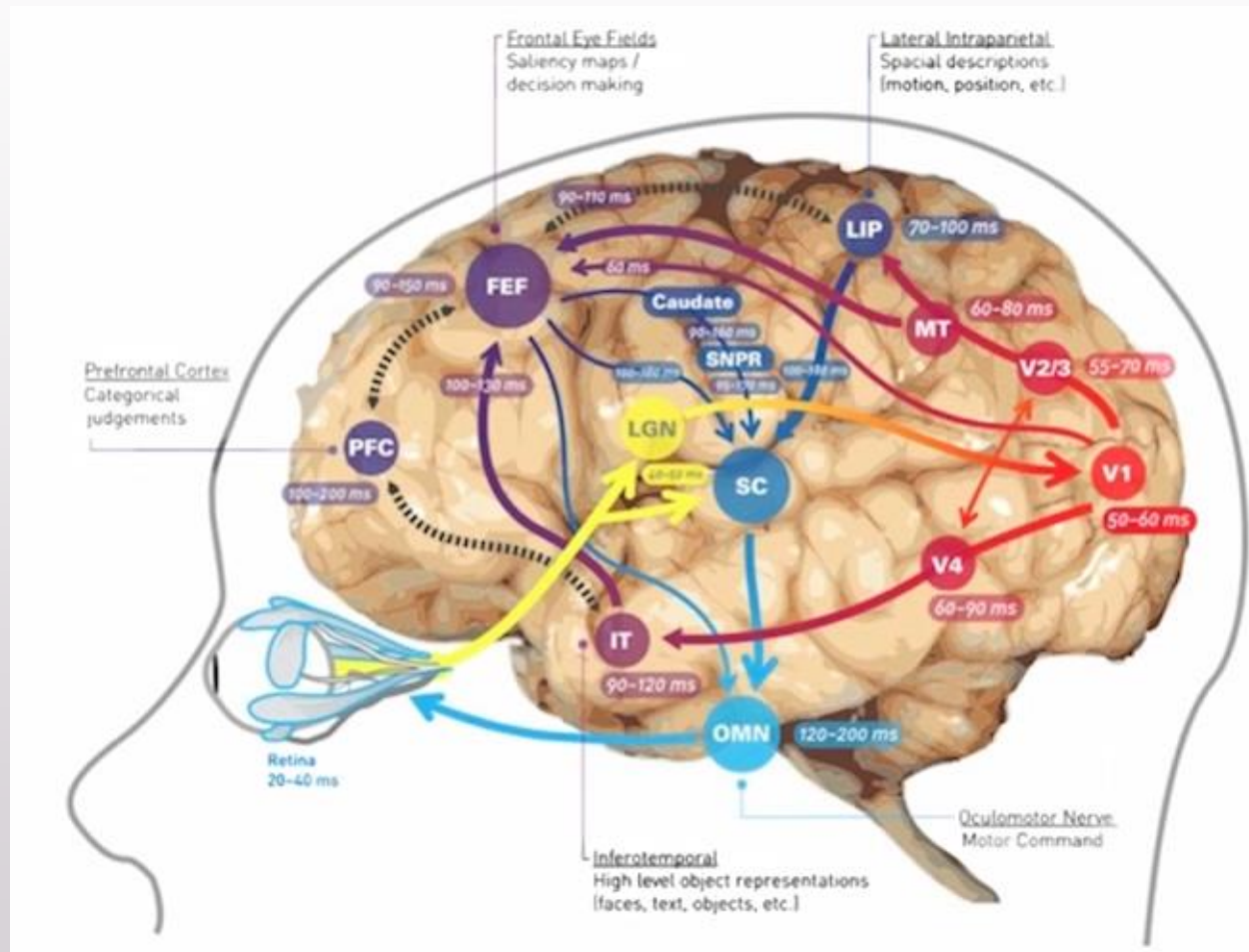
Fig. 1 Processing workflow to create the multiscale probabilistic atlas of the white matter (*MultiConn*). (a) Processing steps applied to each subject. (b) Spatial probability map for a bundle in each of the scales. (c) Atlas-based connectomes computed using the developed multi-scale atlas.

Психо-физиологични експерименти – индиректна информация за работата на МОЗЪКА



Пример: Модел на зрителната система

Това е най-изучаваната система в мозъка от векове, поради което има натрупани литературни за структурите в мозъка, тяхната роля и взаимна свързаност. Моделът ни се основава на тях и използваме само психо-физиологични експерименти



Модел на LGN невроните

Casti, A., Hayot, F., Xiao, Y., Kaplan, E., A simple model of retina-LGN transmission, J. Computational Neuroscience, 2008, vol.24, pp. 235–252

$$C \frac{dV(t)}{dt} = -G_L [V - V_L] - G_E(t) [V - V_E] - G_I(t) [V - V_I] - G_A(t) [V - V_A]$$

$$G_X = \sum_j g_x(t - t_j) H(t - t_j)$$

$$g_x(t) = \bar{g}_x \frac{t}{\tau_x} e^{-\frac{t - \tau_x}{\tau_x}}$$

Модел на невроните в неокортекса

Meffin, H., Burkitt, A. N. and Grayden, D. B., An analytical model for the large fluctuating synaptic conductance state typical of neocortical neurons in vivo, J. Computational Neuroscience, 2004, vol.16, pp.159-175

$$C \frac{dV(t)}{dt} = -G_{rest} [V(t) - V_{rest}] + I_{syn}$$

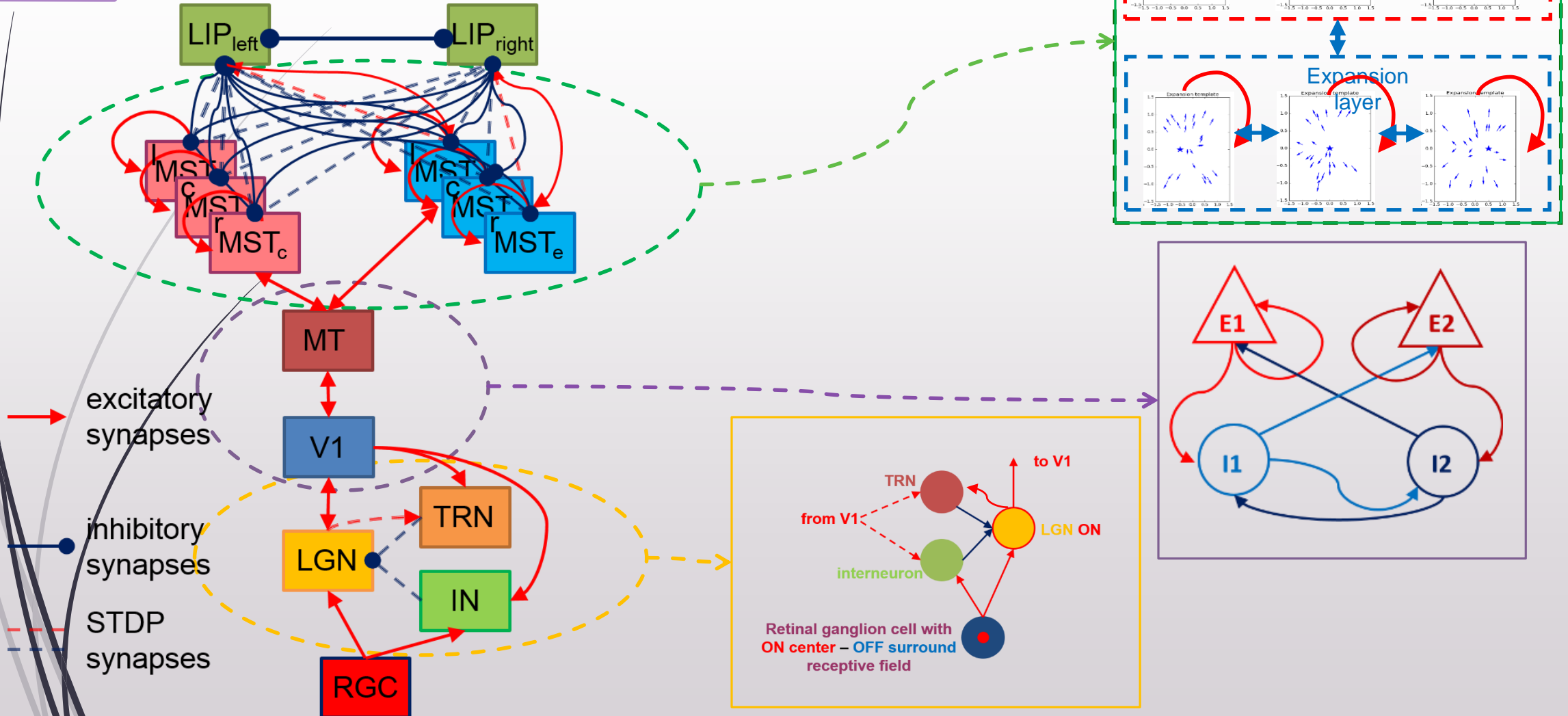
$$I_{syn} = C \sum_{k=I,E} G_k(t) (V - V_k)$$

$$\frac{dG_k}{dt} = -\frac{G_k}{\tau_k} + g_k P_k(t)$$

$$P_k(t) = \sum_n \delta(t - t_n - \tau_k)$$

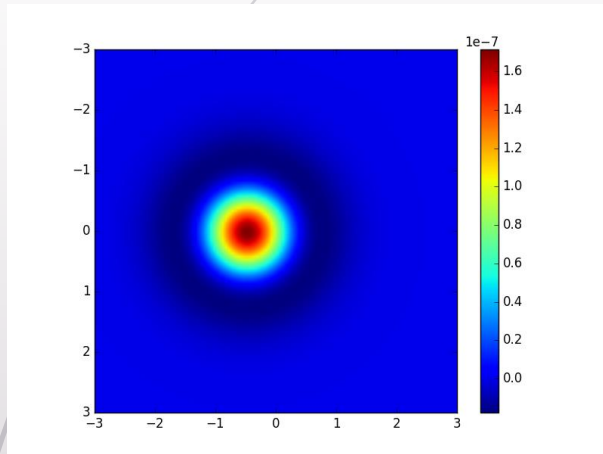
Модел на зрителната система

Възприятие



Рецепторни полета на фоточувствителните рецептори в ретината

ON

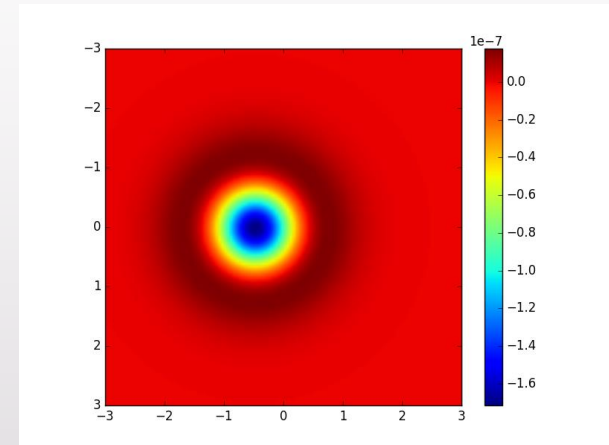


$$RF = C - S$$

$$C = \frac{a_C}{\sigma_C^2} e^{-\frac{R}{\sigma_C^2}}$$

$$S = \frac{a_S}{\sigma_S^2} e^{-\frac{R}{\sigma_S^2}}$$

OFF



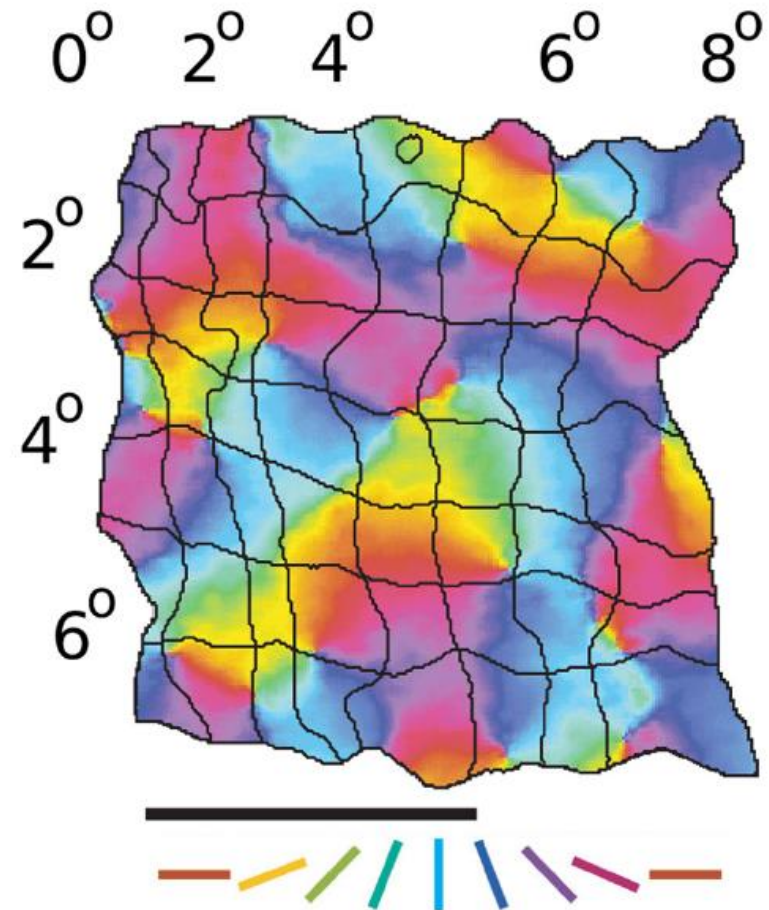
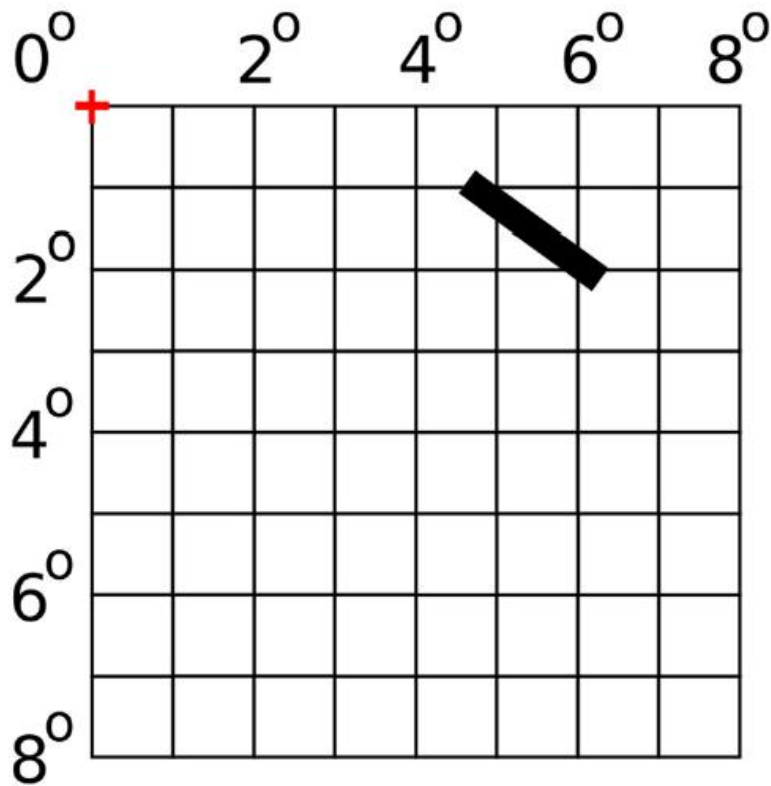
$$R = \sqrt{(X - X_{RF})^2 + (Y - Y_{RF})^2}$$

$$X = X \cdot \cos \theta + Y \cdot \sin \theta$$

$$Y = -X \cdot \sin \theta + Y \cdot \cos \theta$$

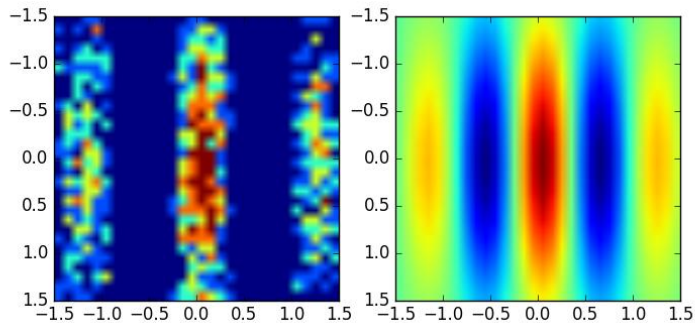
$$\sigma_C = rf_{scale} \sigma_C^{base} \quad \sigma_S = rf_{scale} \sigma_S^{base}$$

Структура и чувствителност в първичната зрителна кора



Рецепторни полета на невроните в първичната зрителна кора

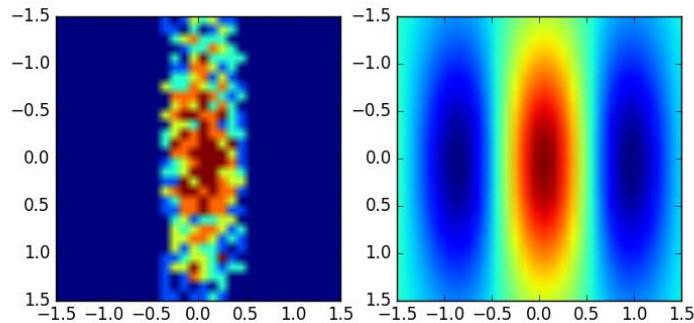
$w=0.8 \theta=0 \varphi=0 \sigma=1.0$



Weights

Gabor filter

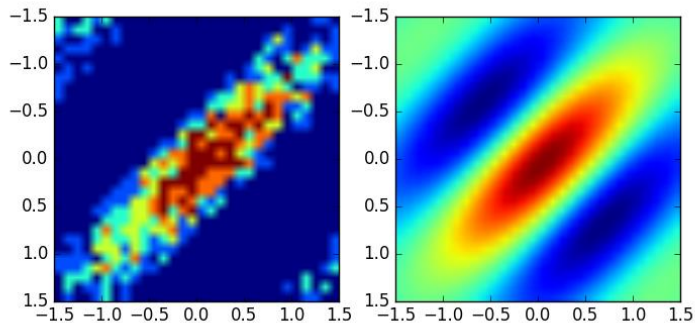
$w=0.5 \theta=0 \varphi=0 \sigma=1.0$



Weights

Gabor filter

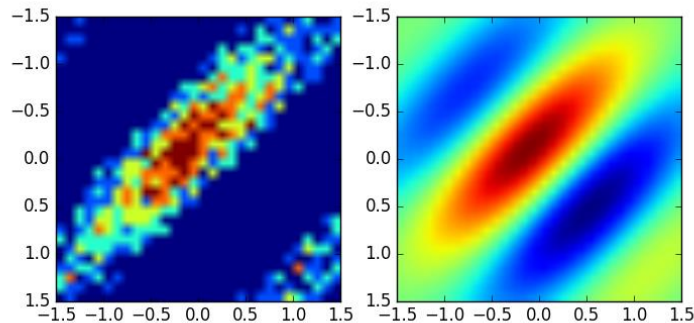
$w=0.5 \theta=45 \varphi=0 \sigma=1.0$



Weights

Gabor filter

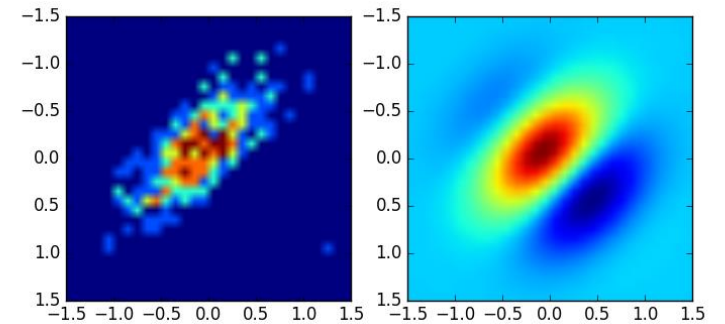
$w=0.5 \theta=45 \varphi=45 \sigma=1.0$



Weights

Gabor filter

$w=0.5 \theta=45 \varphi=45 \sigma=0.5$

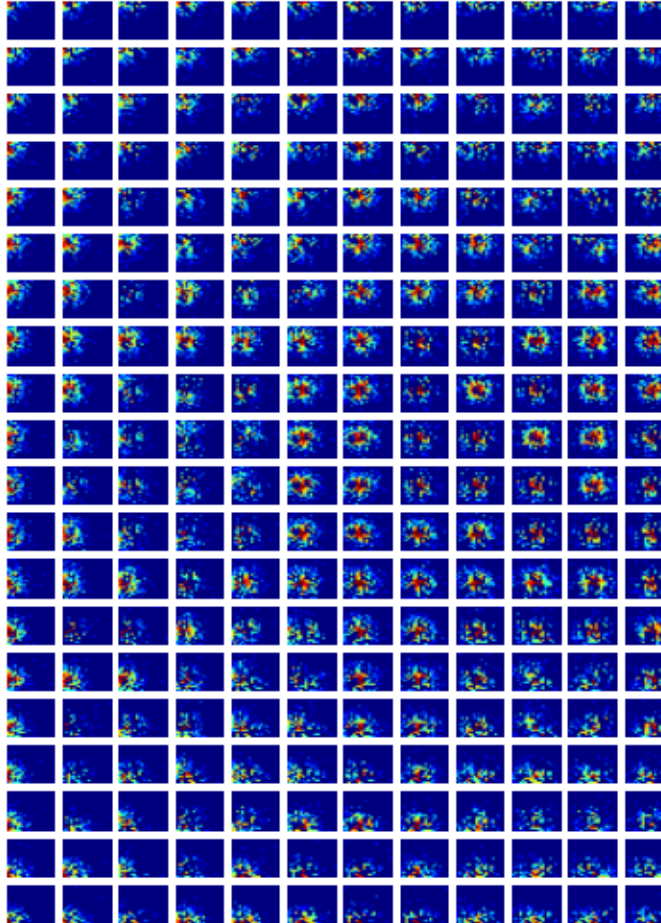


Weights

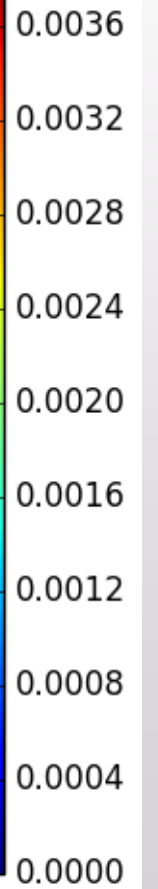
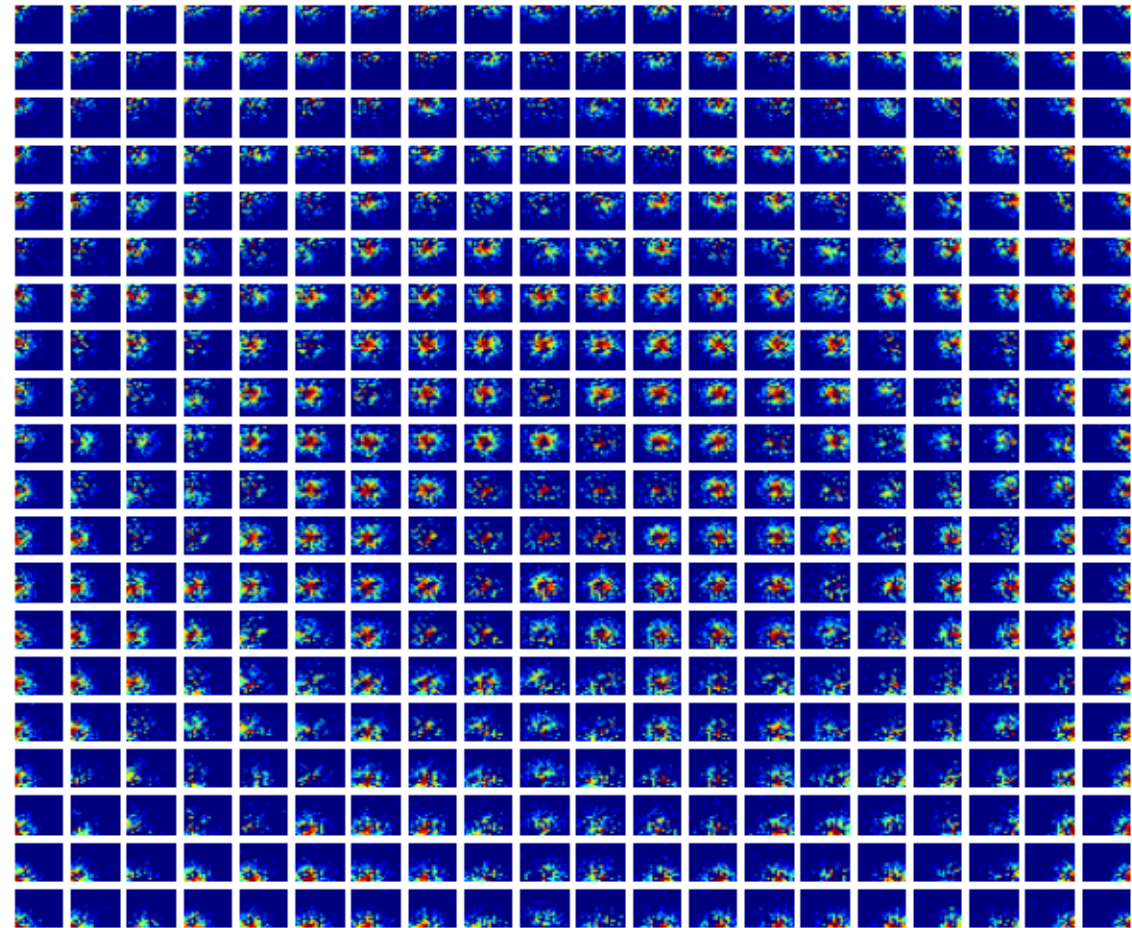
Gabor filter

Латерални връзки в V1

Excitatory connections from E1 to E1

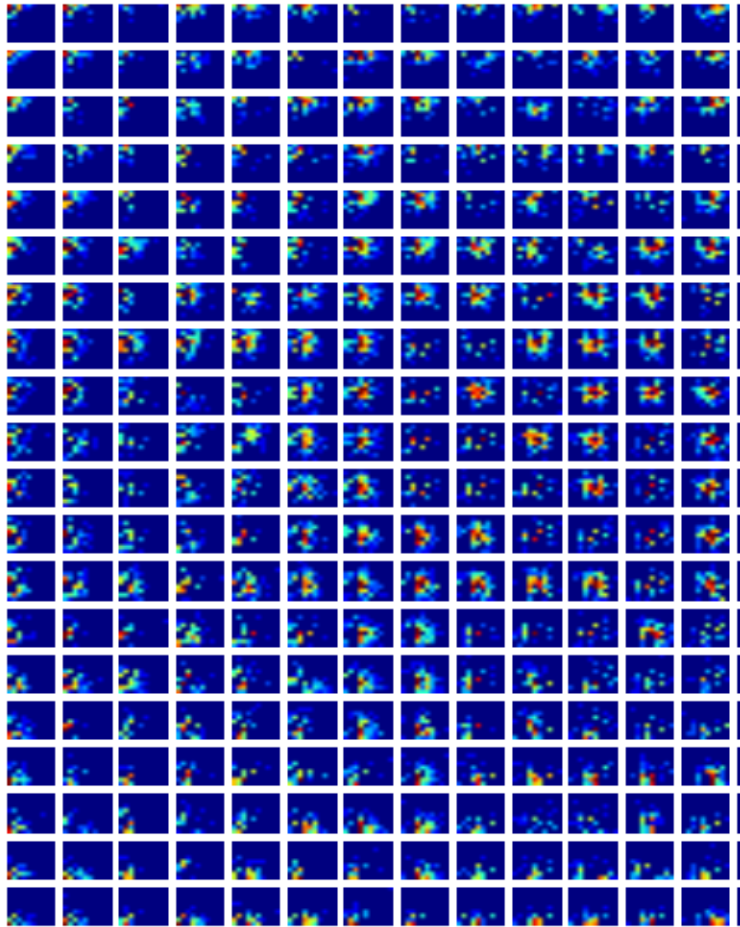


Excitatory connections from E2 to E2

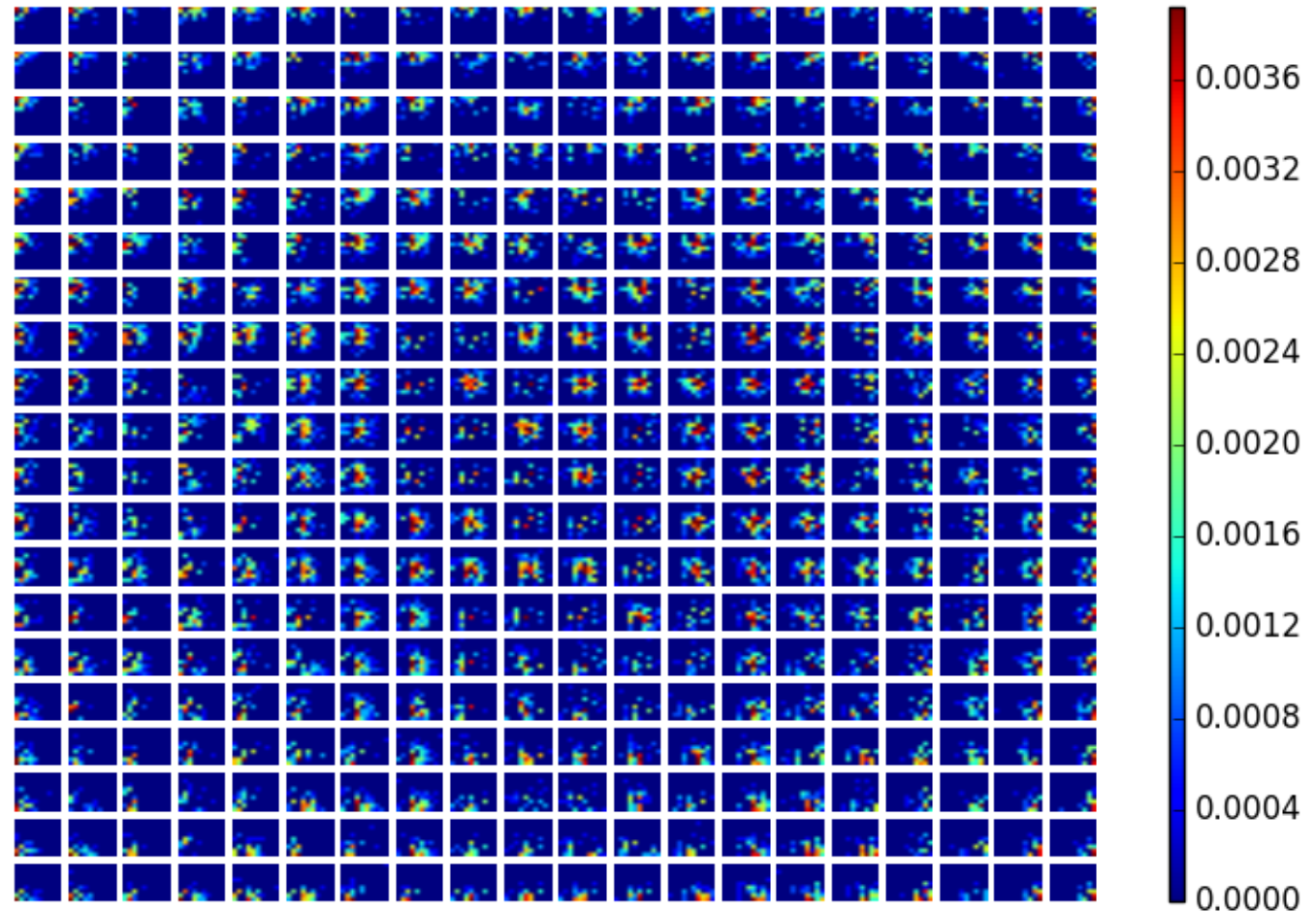


Латерални връзки в V1

Excitatory connections from E1 to I1

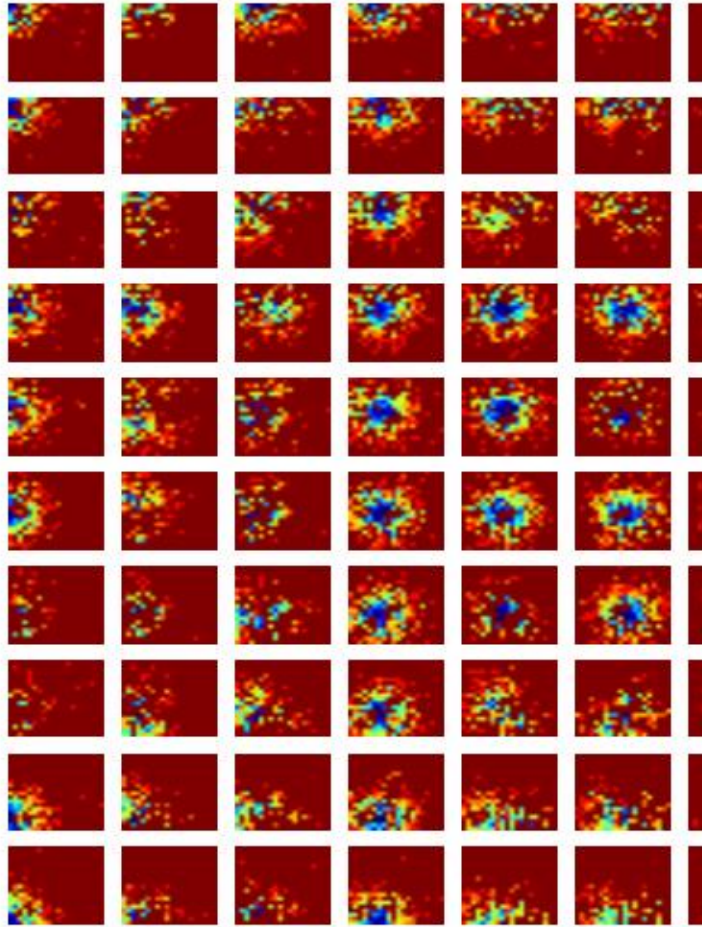


Excitatory connections from E2 to I2

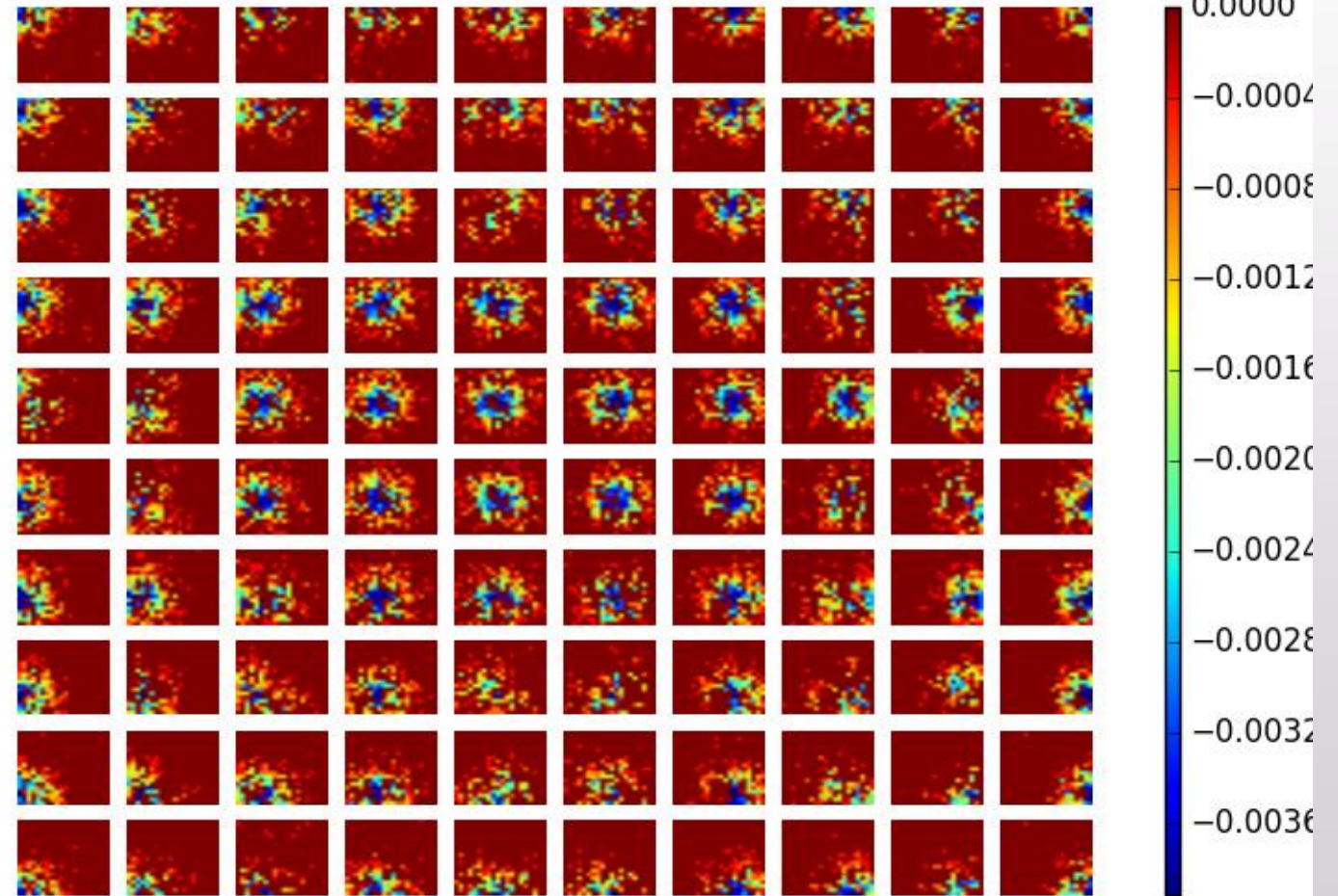


Латерални връзки в V1

Inhibitory connections from I1 to E2

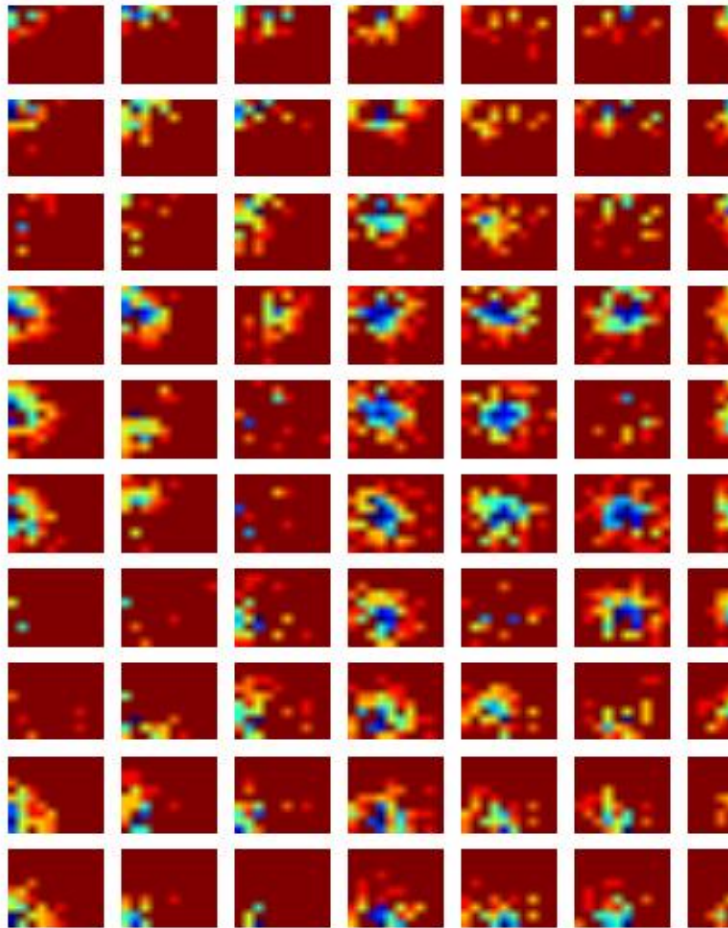


- 0.0000
Inhibitory connections from I2 to E1

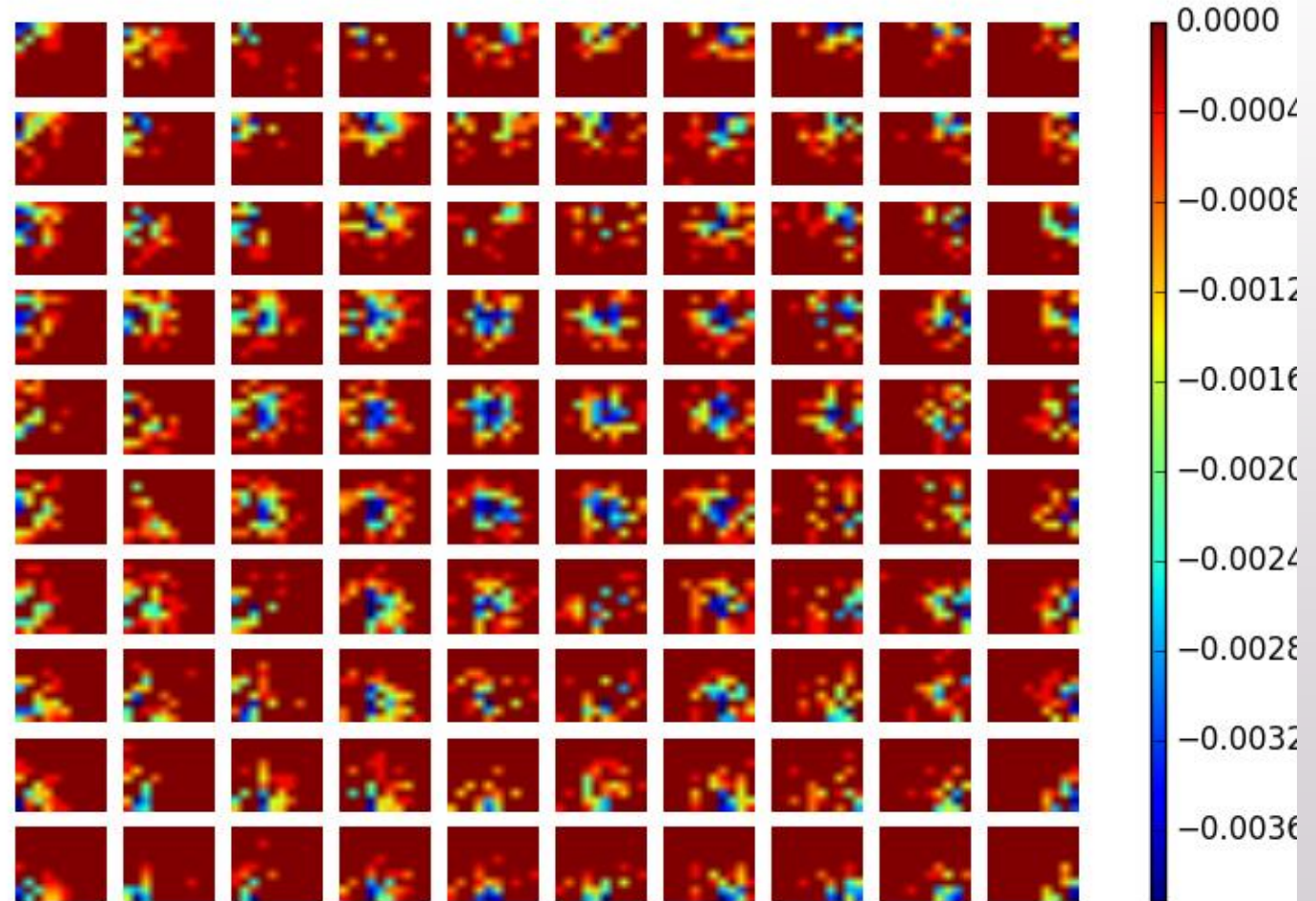


Латерални връзки в V1

Inhibitory connections from I1 to I2

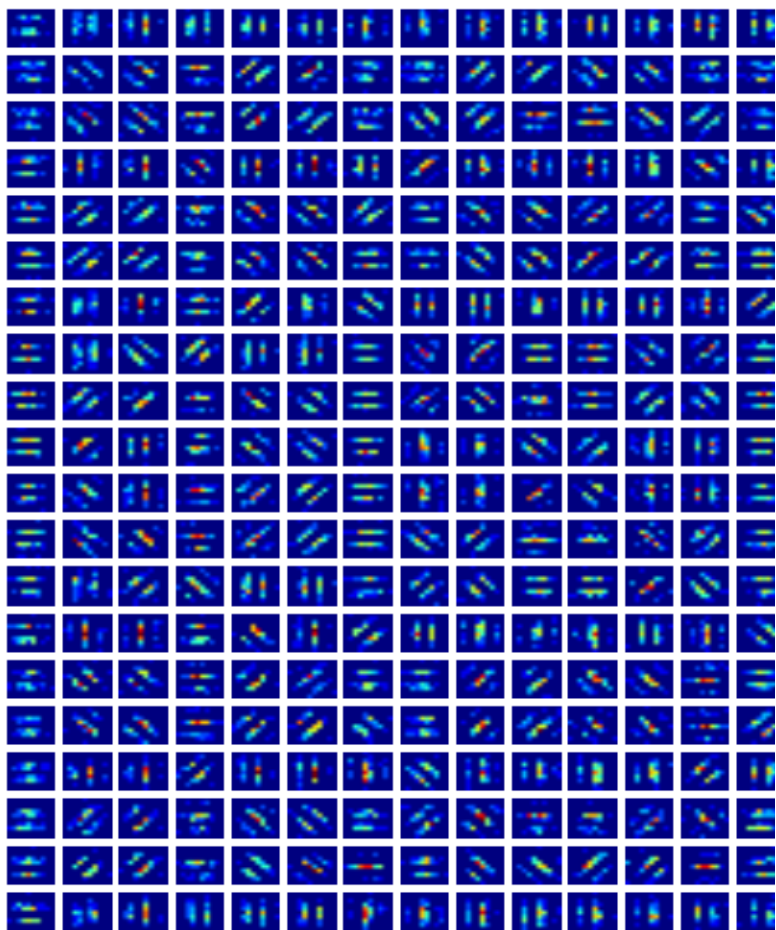


Inhibitory connections from I2 to I1

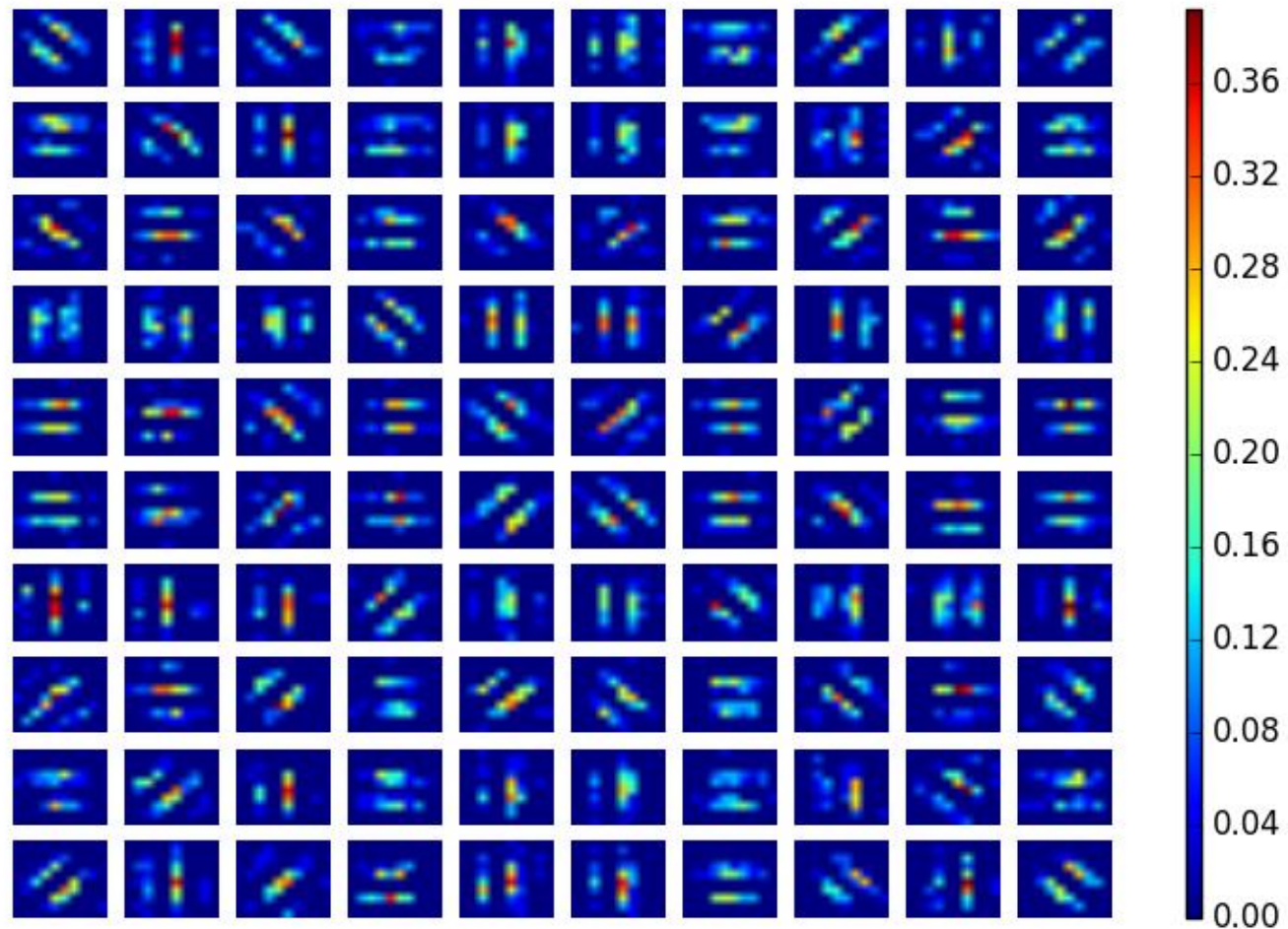


Връзки между таламуса и V1

Receptive fields of E1 from LGN ON1

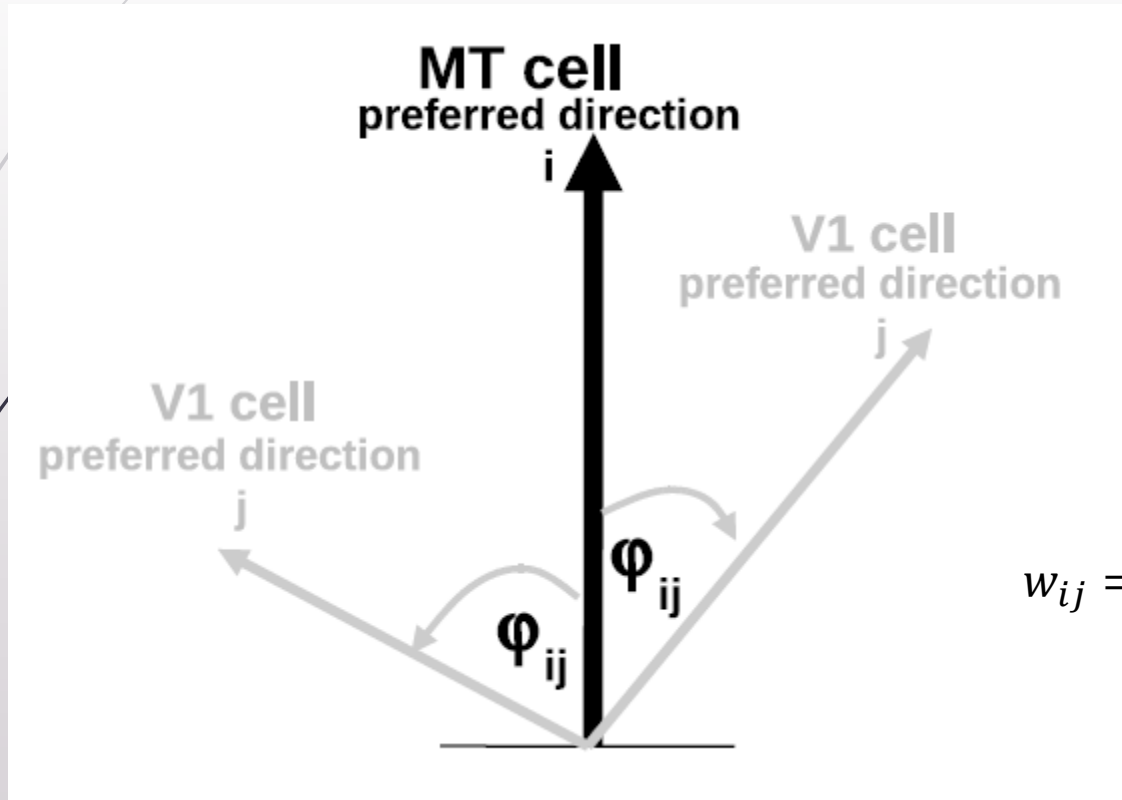


Receptive fields of I1 from LGN ON1



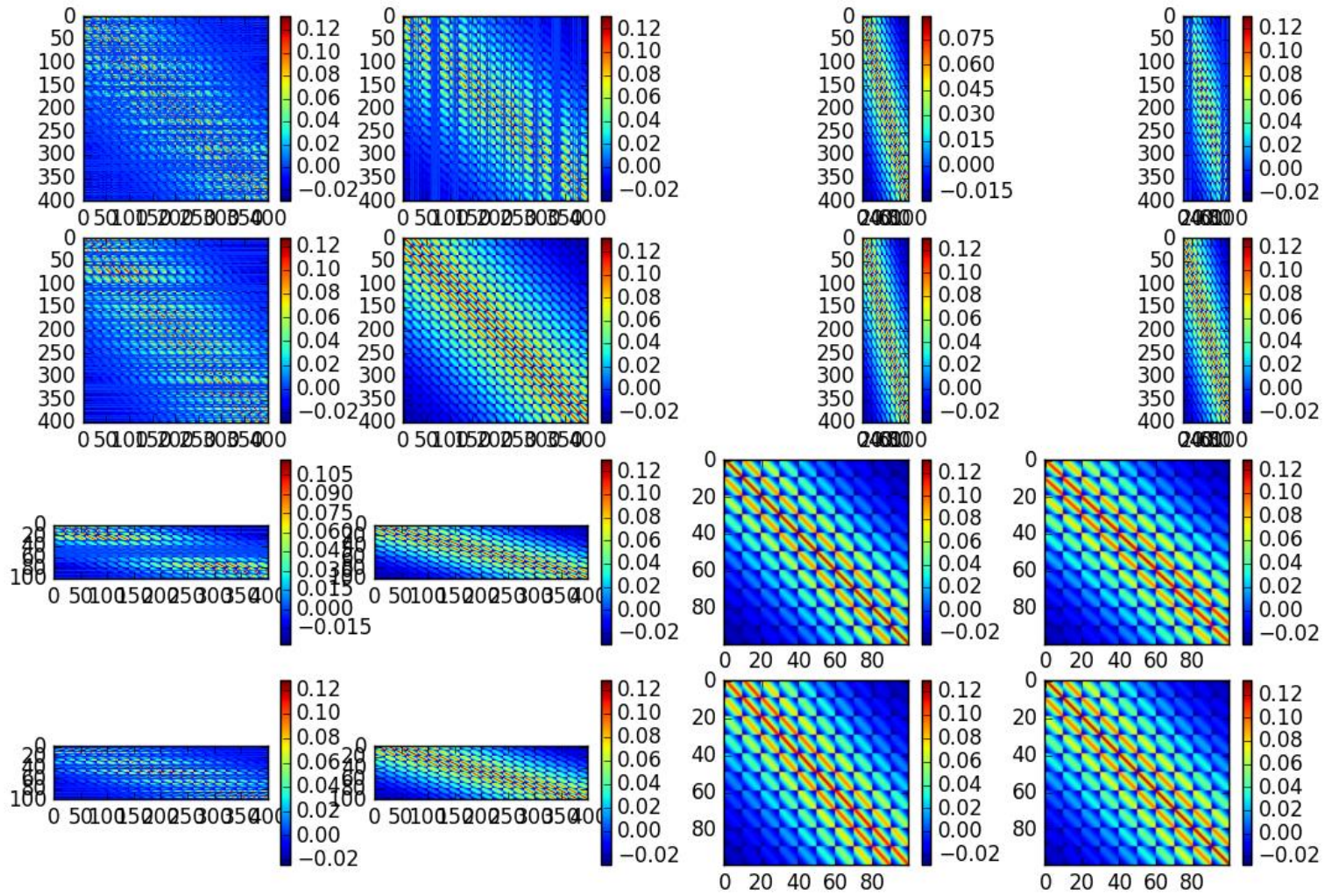
Структура на МТ

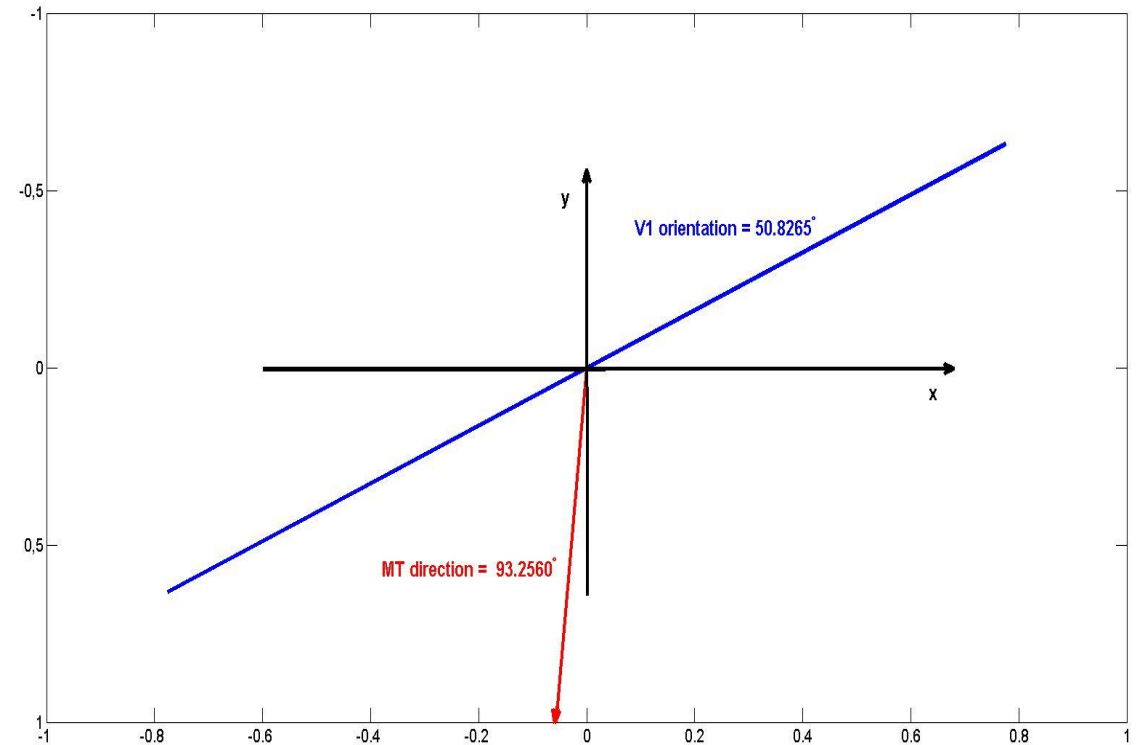
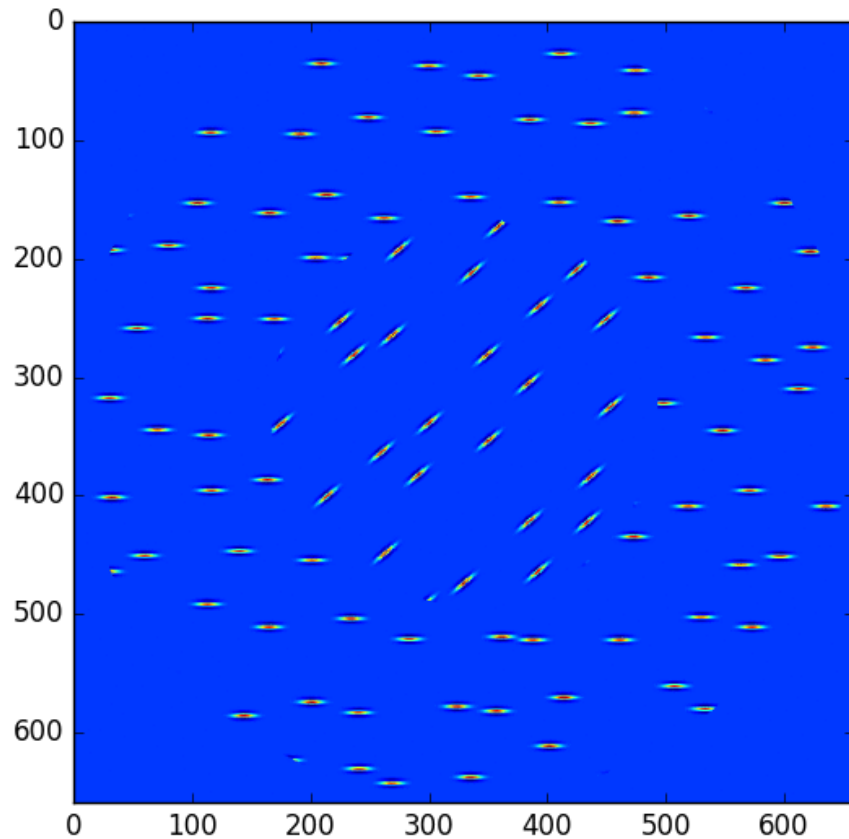
M.-J. Escobar, G. S. Masson, T. Vieville, P. Kornprobst, Action Recognition Using a Bio-Inspired Feedforward Spiking Network, Int J Comput Vis (2009) 82: 284–301



$$w_{ij} = \begin{cases} k_c w_{cs} (x_i^{MT} - x_j^{V1}) \cos \varphi_{ij}, & 0 \leq \varphi_{ij} \leq \frac{\pi}{2} \\ 0, & \frac{\pi}{2} < \varphi_{ij} < \pi \end{cases}$$

Връзки от V1 към МТ

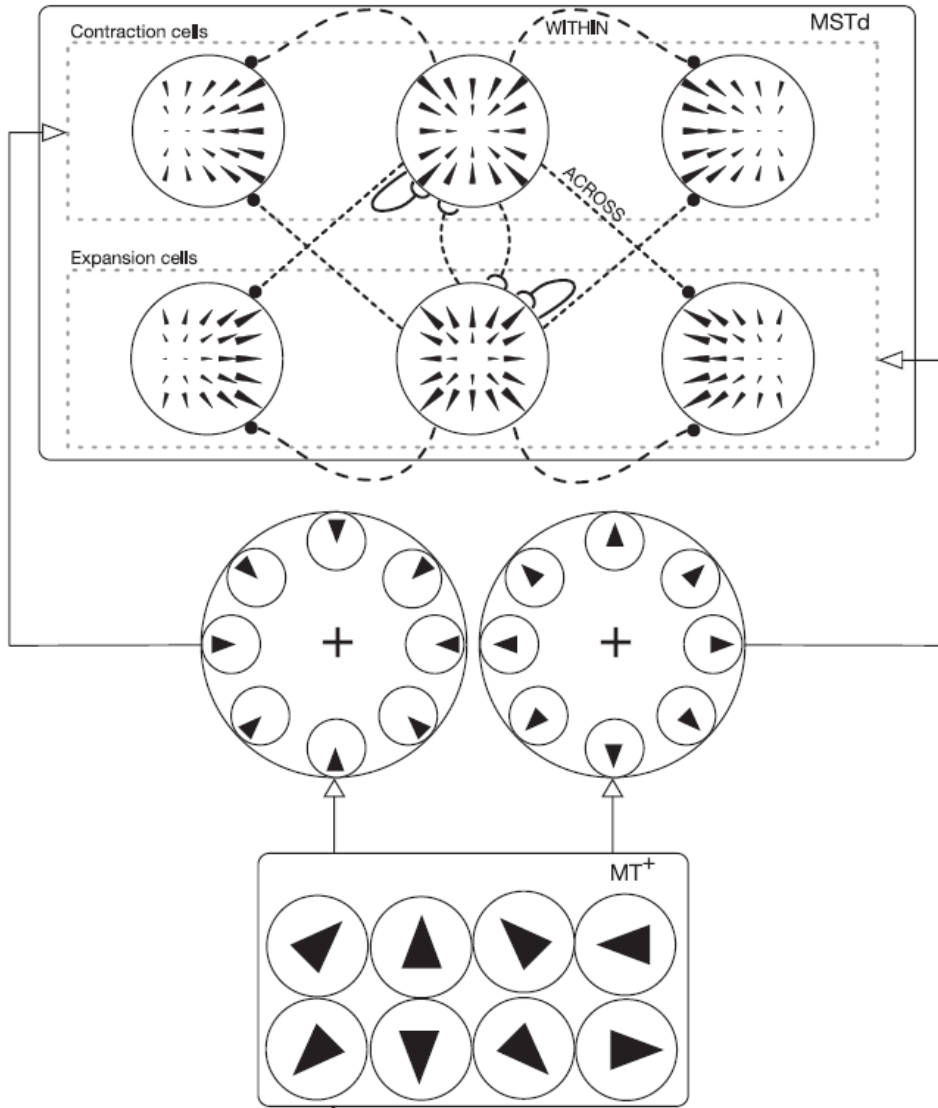




$$OR_{est} = \arctg \frac{\sum_i n_i \sin \theta_i}{\sum_i n_i \cos \theta_i}$$

MSTd структура

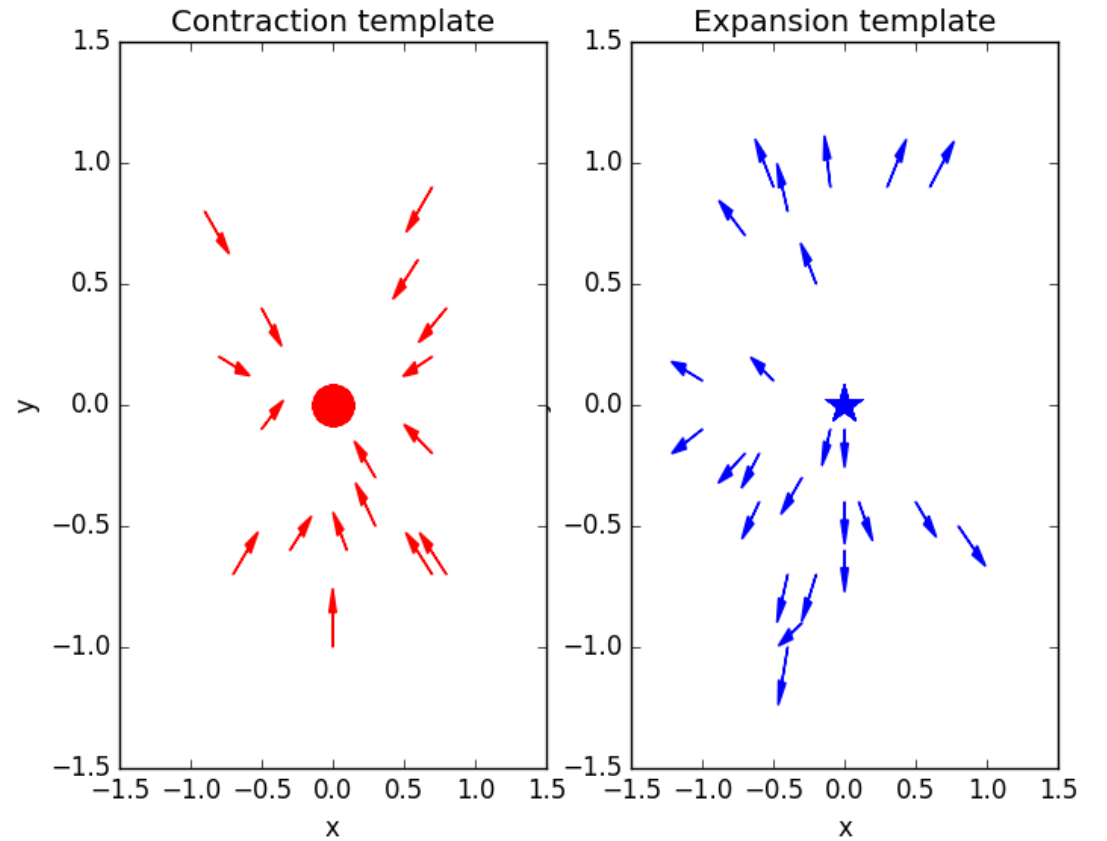
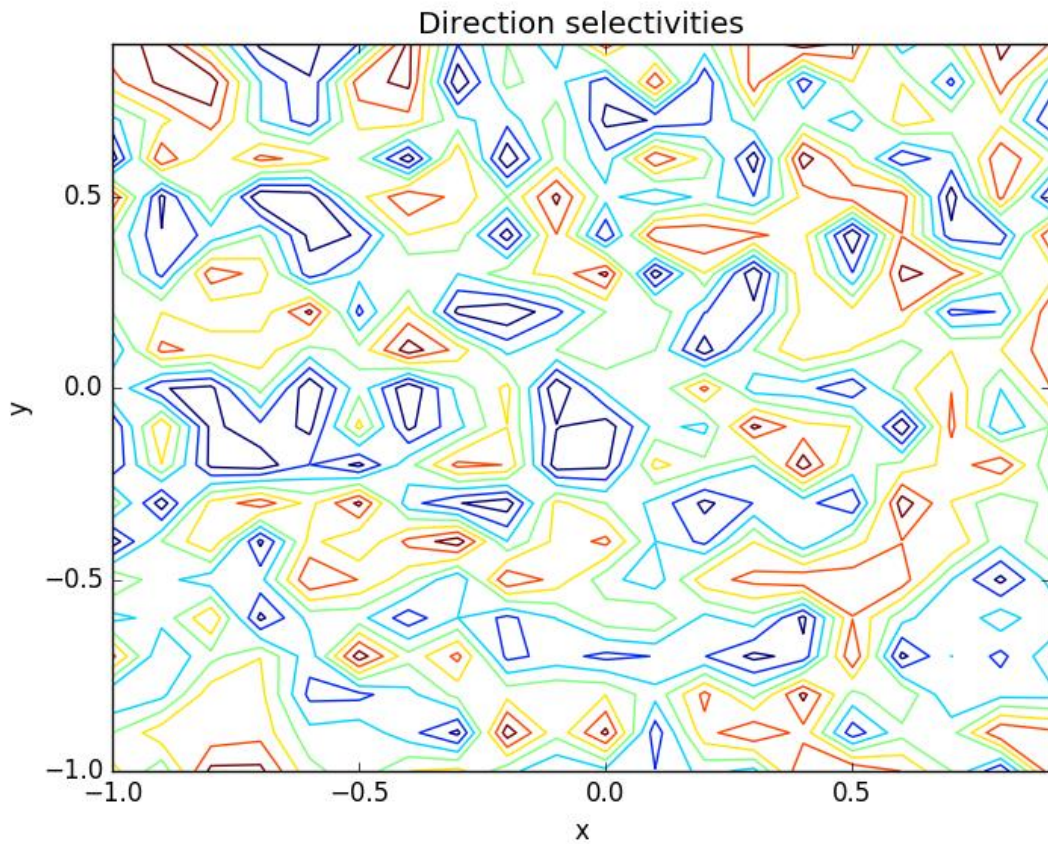
Layton, O. W., Fajen, B. R., Possible role for recurrent interactions between expansion and contraction cells in MSTd during self-motion perception in dynamic environments, Journal of Vision (2017) 17(5):5, 1–21



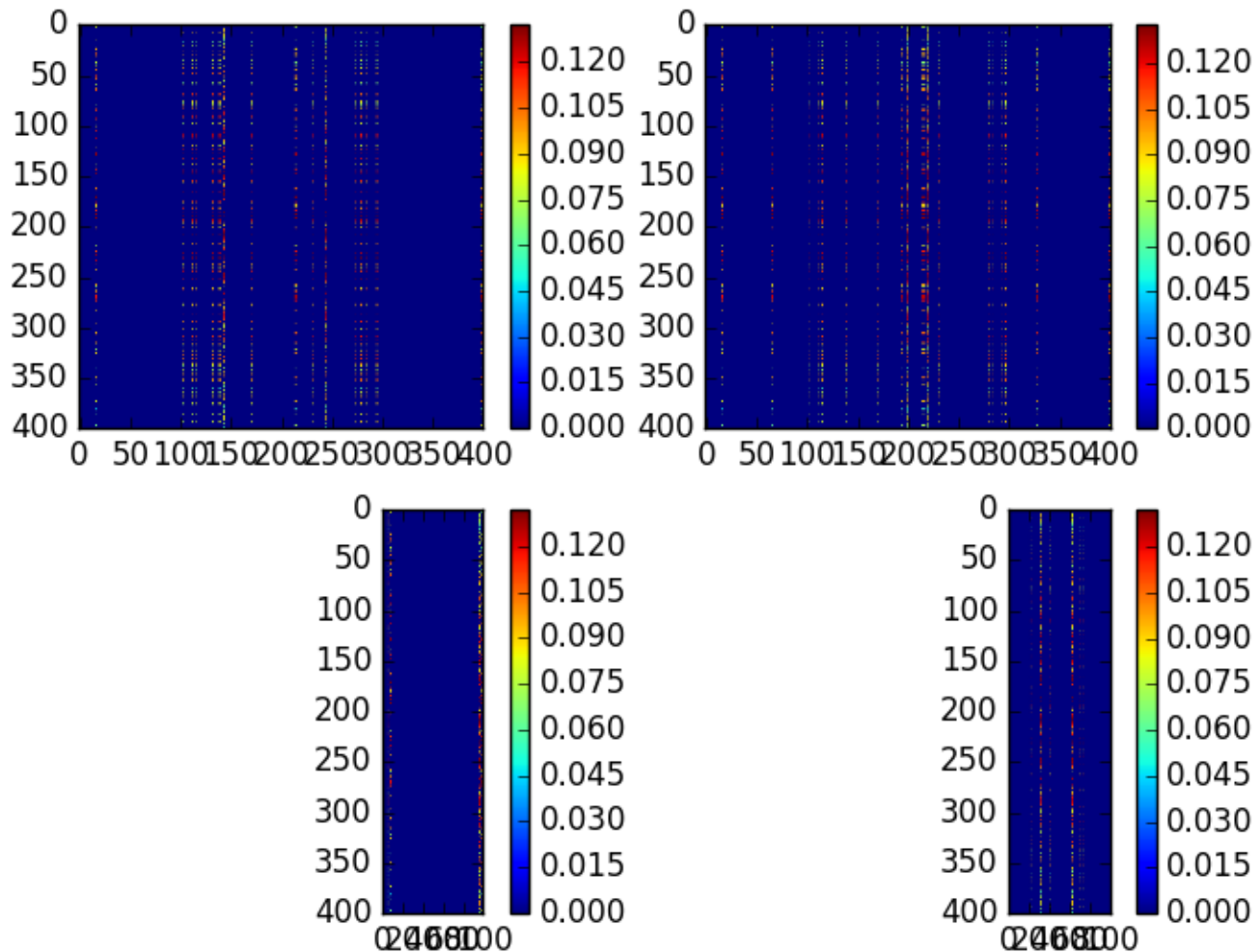
$$T_{e(c)}(x_{MT}, y_{MT}, x_{MSTd}, y_{MSTd}, \theta) = e^{-d((x_{MT} - x_{MSTd})^2 + (y_{MT} - y_{MSTd})^2)} \Gamma$$

$$T = \begin{cases} 1, & \delta \text{ is in range} \\ 0 & \text{otherwise} \end{cases}$$

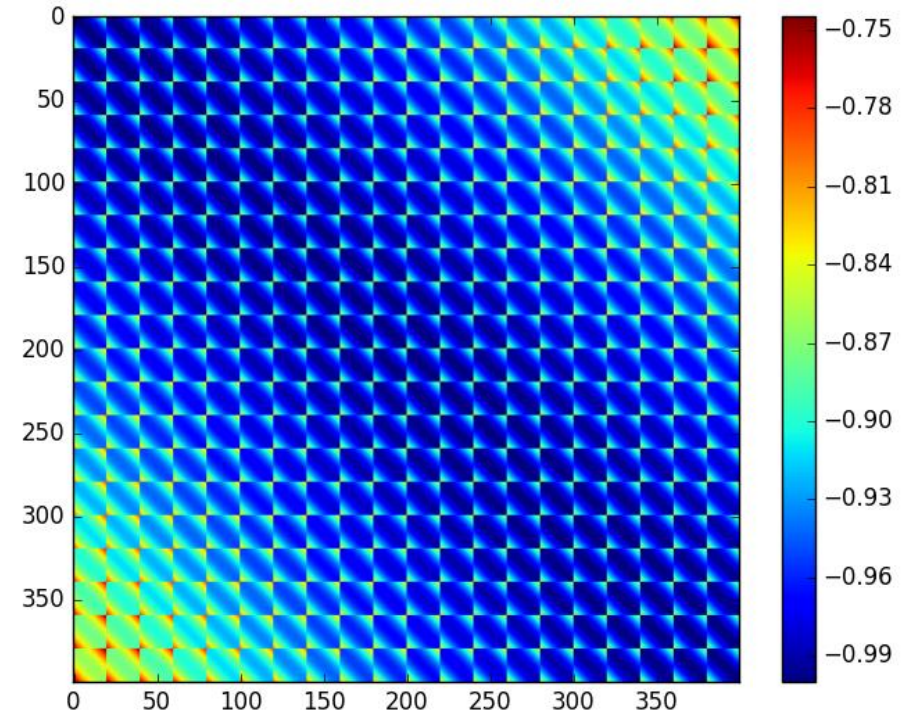
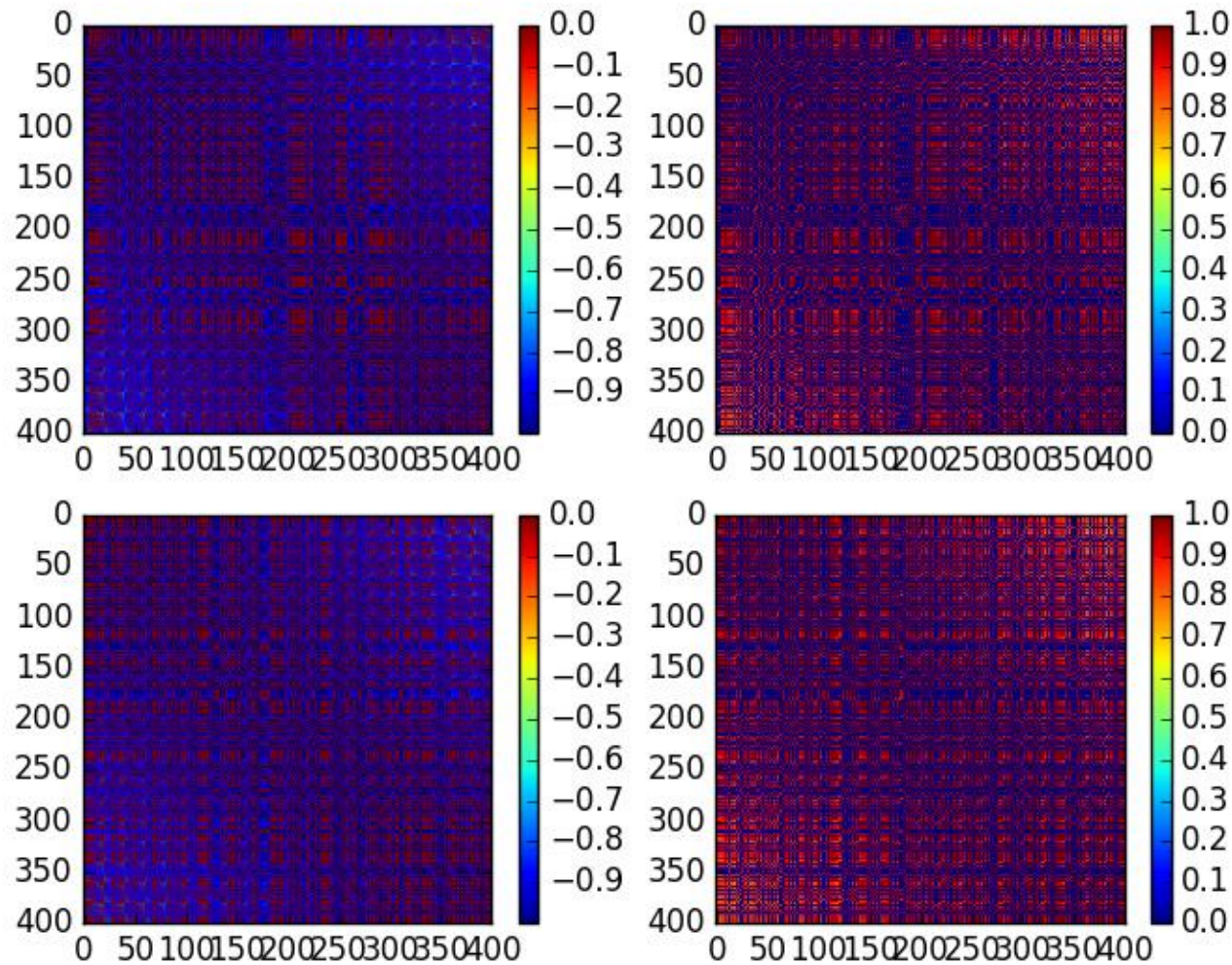
$$\delta = \arctg \frac{y_{MT} - y_{MSTd}}{x_{MT} - x_{MSTd}}$$



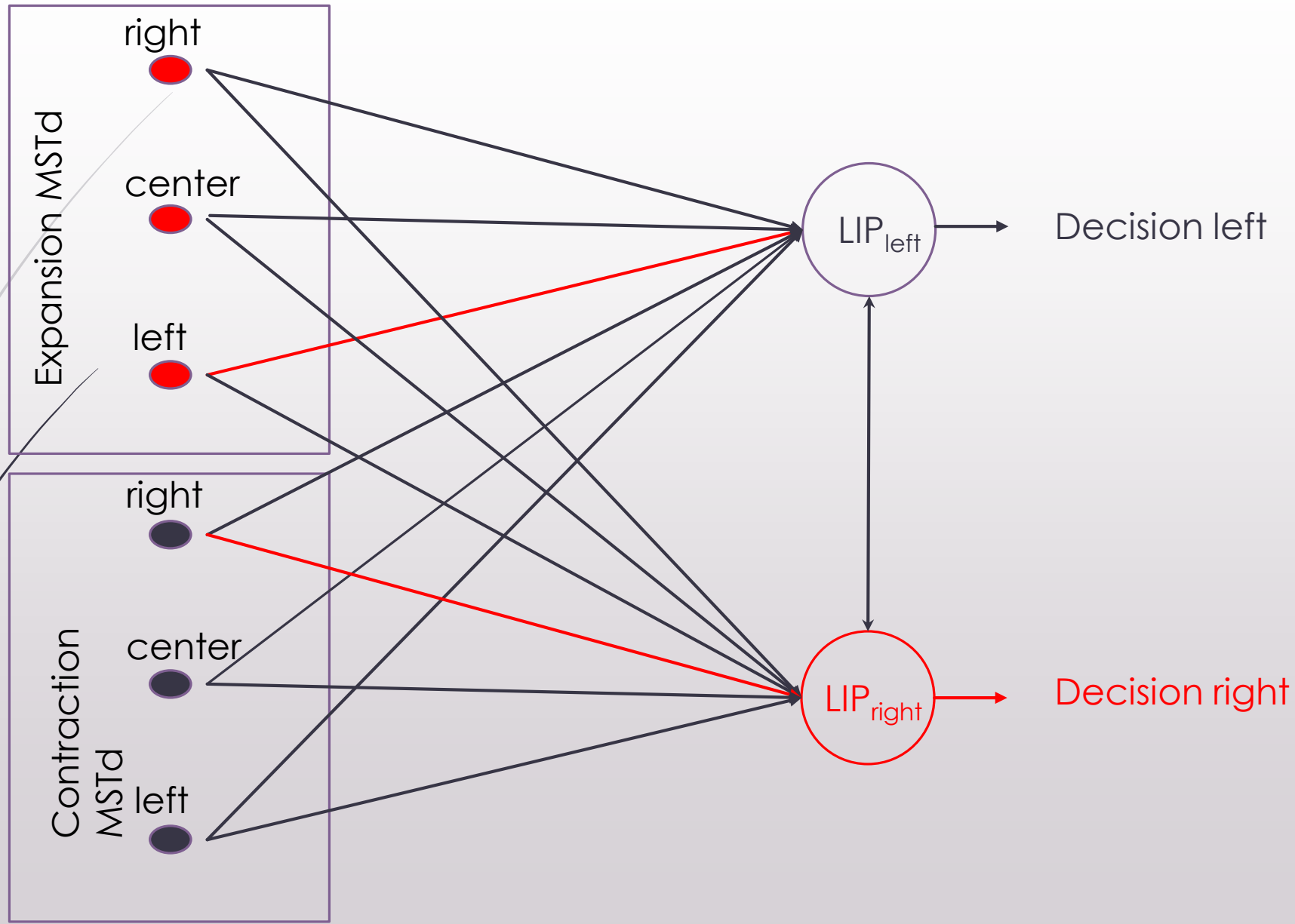
MT към MSTd връзки

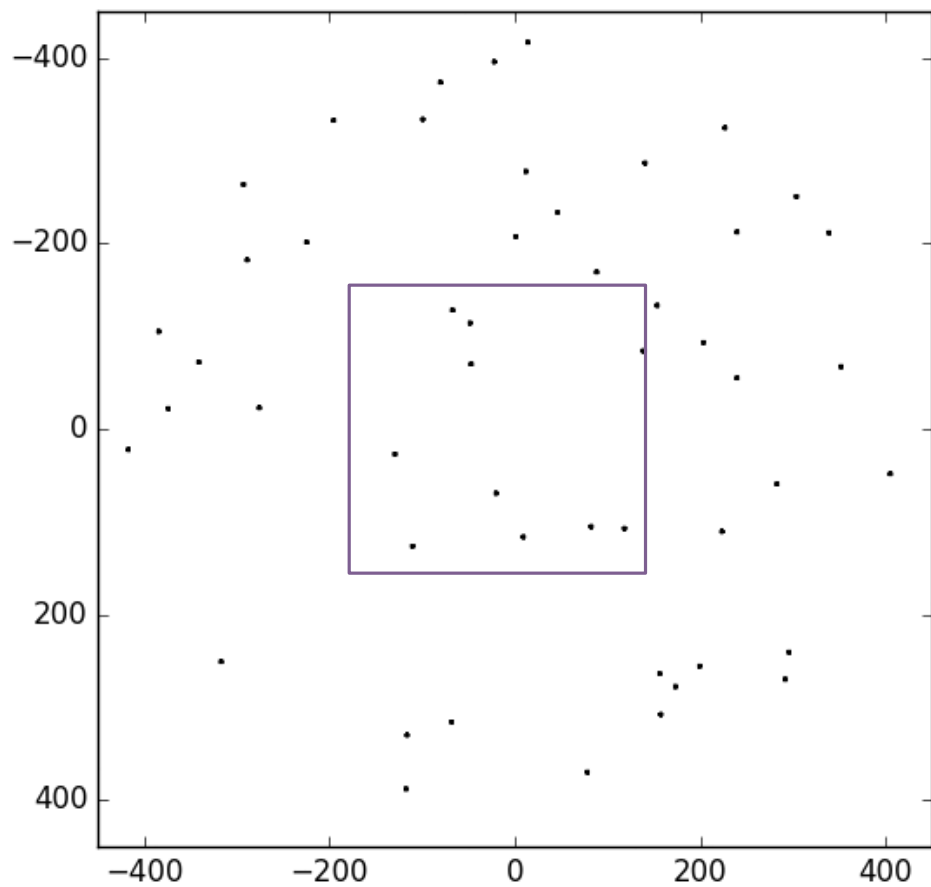


MSTd латерални врџки

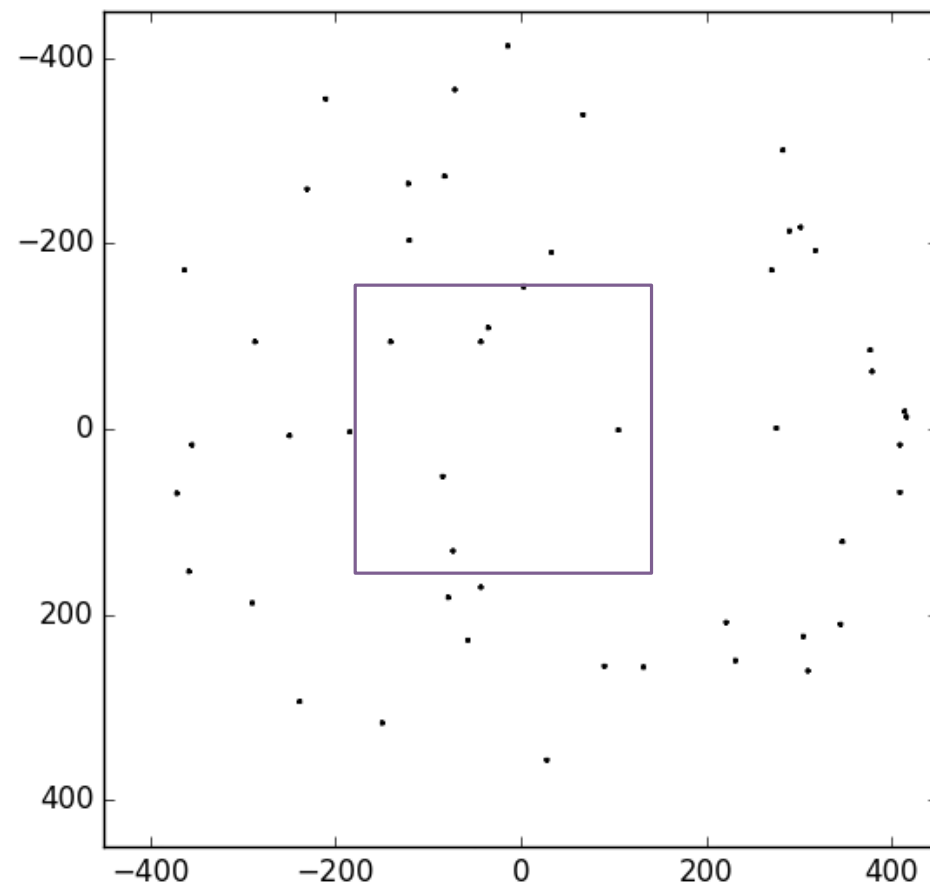


LIP структура

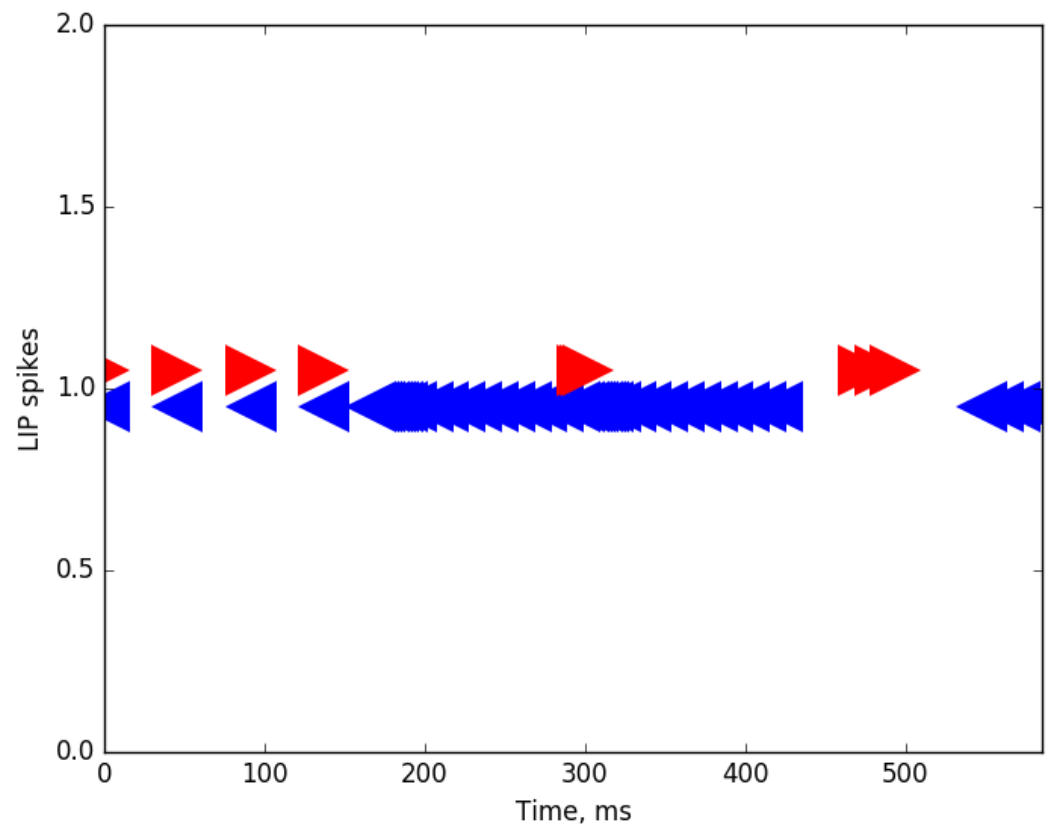




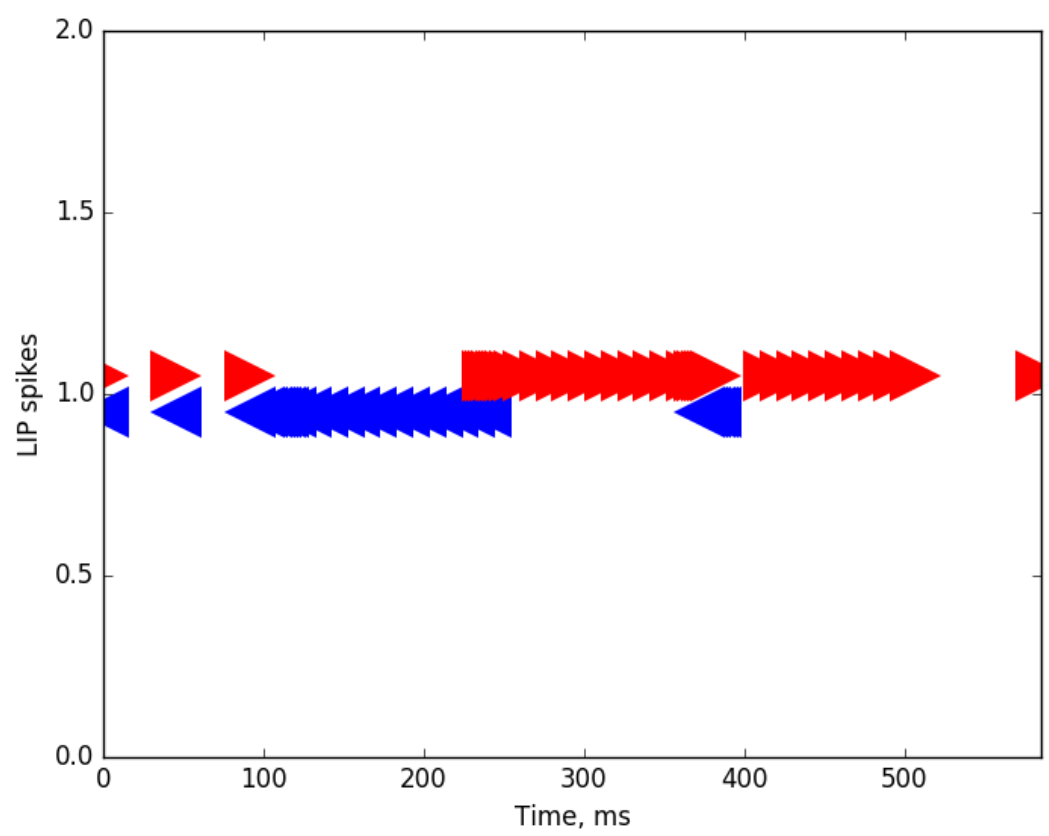
left



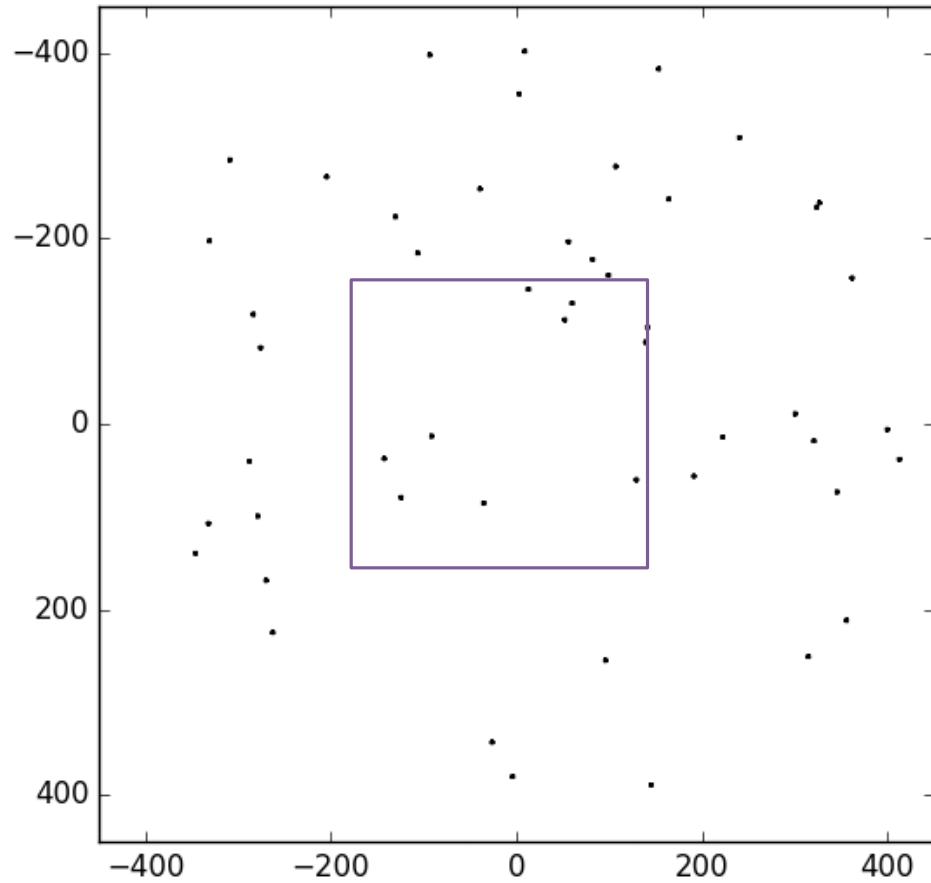
right



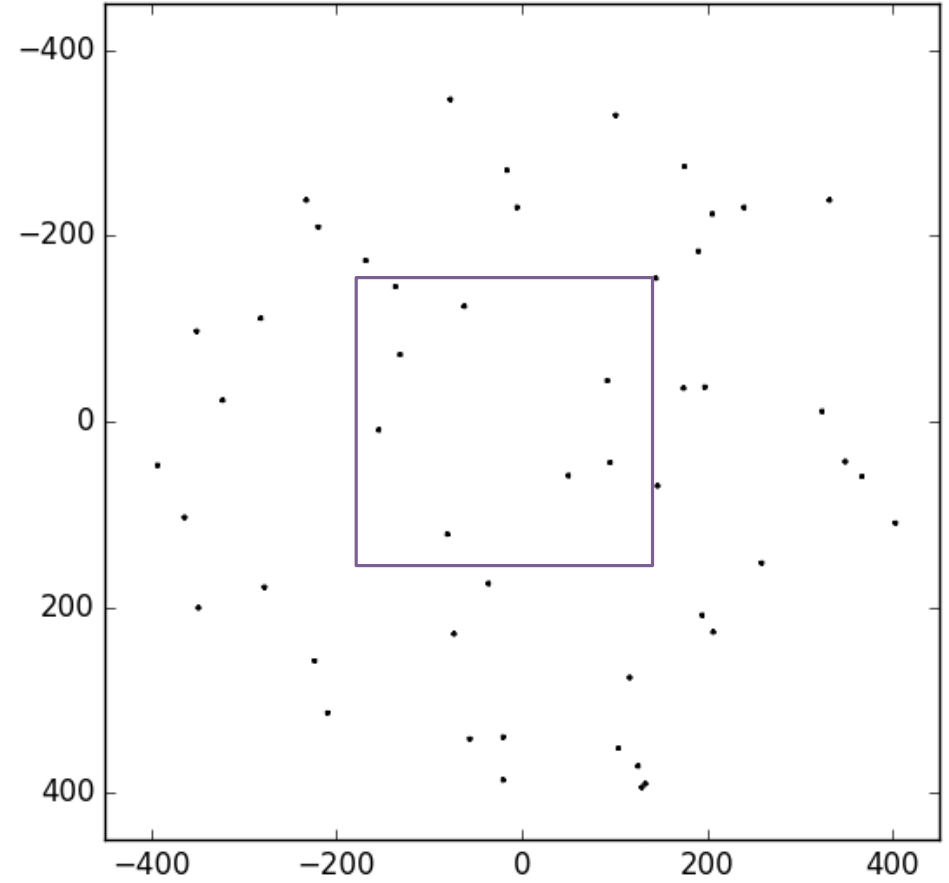
left



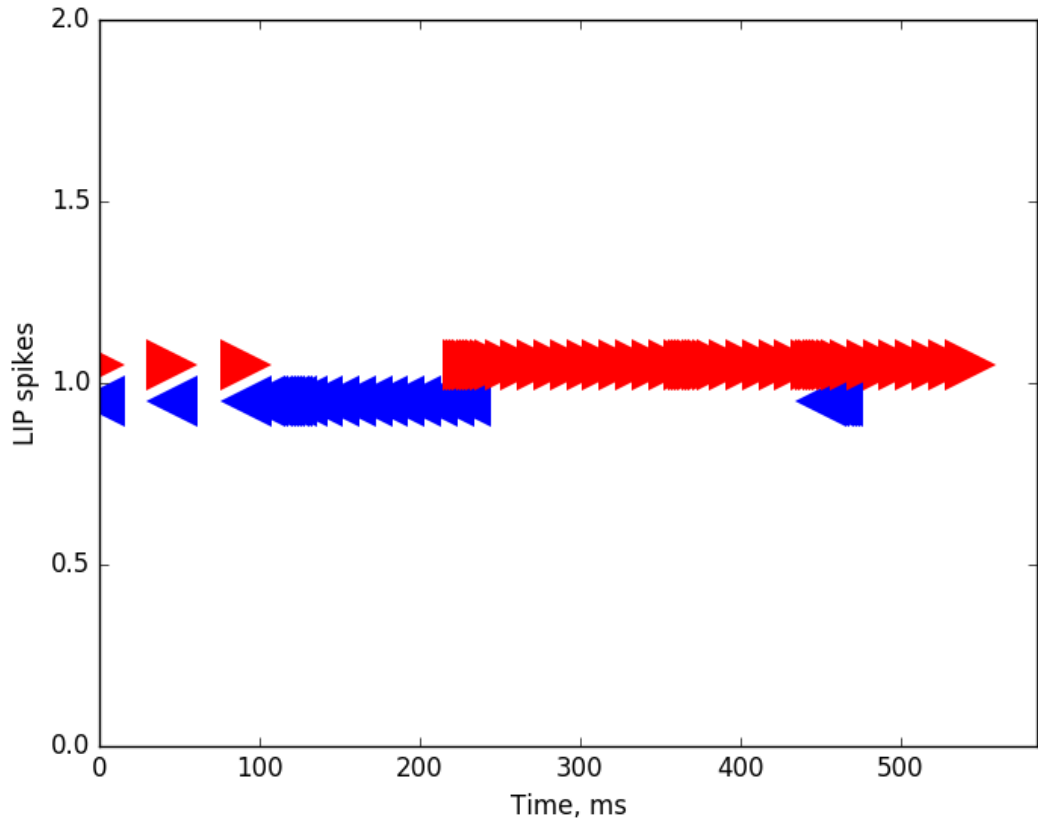
right



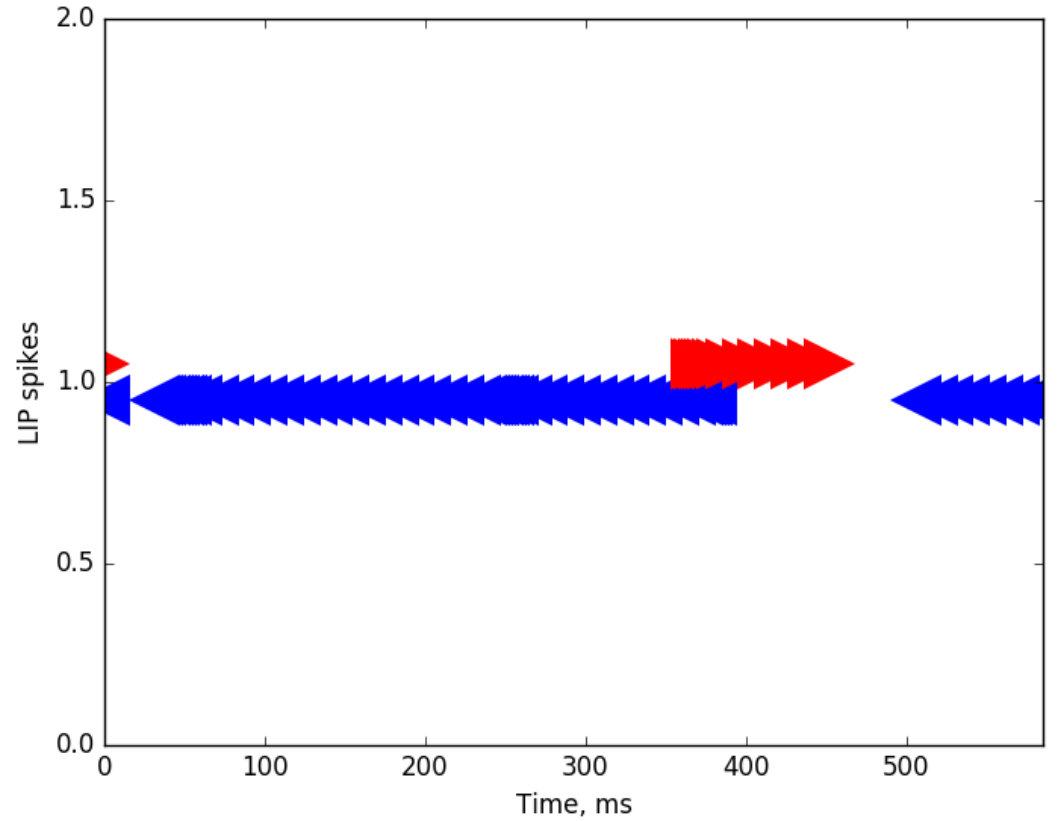
left



right



left



right

Връзки в базалните ганглии

LIP to Stratum (D1 and D2): all-to-all interlayer connections

Stratum (D1 and D2) and SNr: lateral connections with short-range excitation and long-range inhibition

$$w_{ij,pq} = Ae^{-\frac{d^2}{2\sigma^2}} - C \quad d = \sqrt{(x_i - x_p)^2 + (y_i - y_p)^2}$$

GPe: lateral connections with negative center and positive surround shape

$$w_{ij,pq} = C - Ae^{-\frac{d^2}{2\sigma^2}}$$

GPe/STN pairs; D1 to SNc and D2 to GPe : one-to-one interlayer connections

GPe_{left} to/from GPe_{right} , SNr to SC and LIP to SC: short-range excitation and long-range inhibition connections

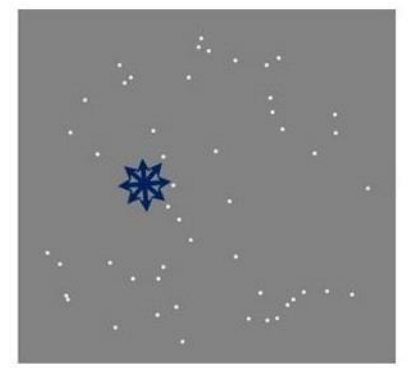
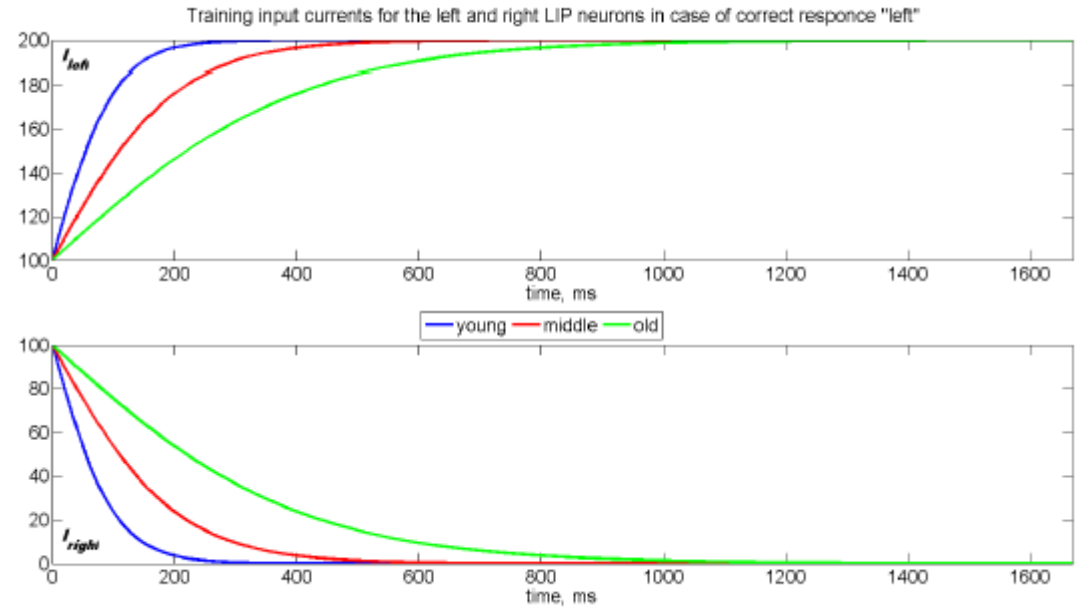
Dopamine synapses:

$$STDP(\Delta t) = \begin{cases} A_+ e^{-|\Delta t|/\tau_+} & \Delta t > 0 \\ A_- e^{-|\Delta t|/\tau_-} & \Delta t \leq 0 \end{cases} \quad A_+, A_- > 0$$

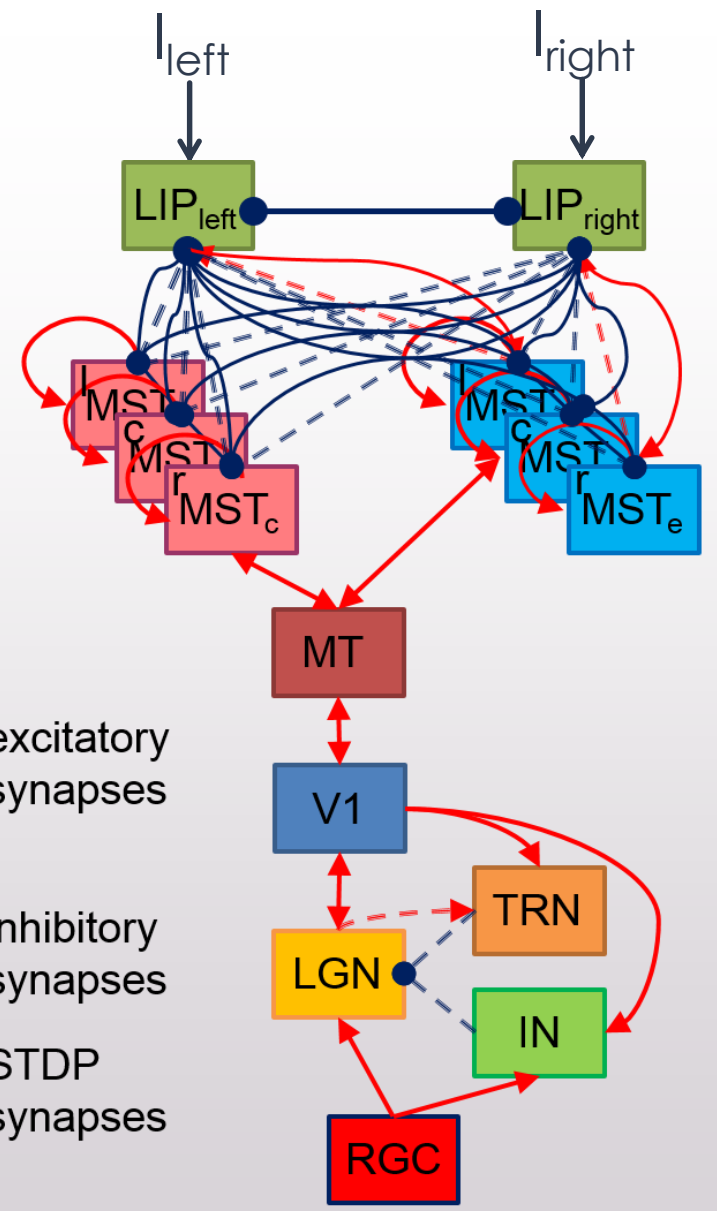
Anti-dopamine synapses:

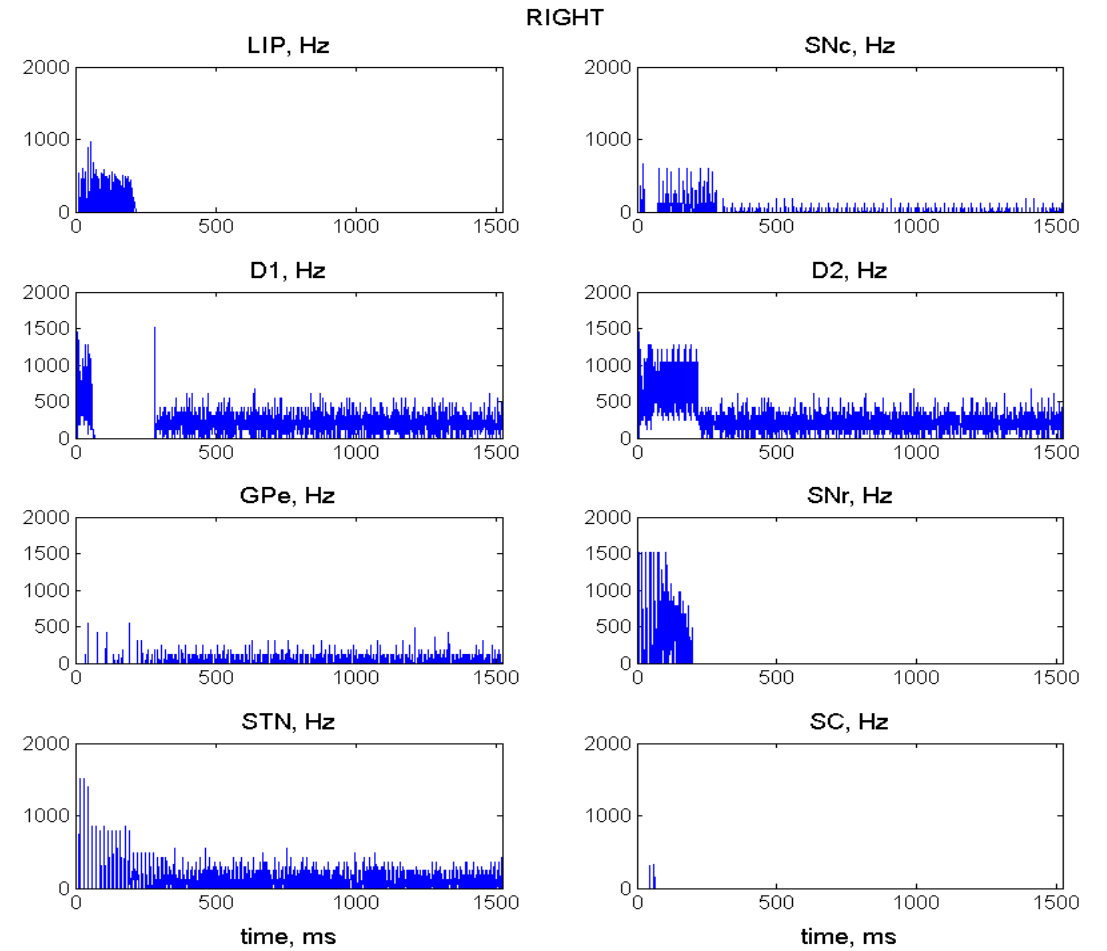
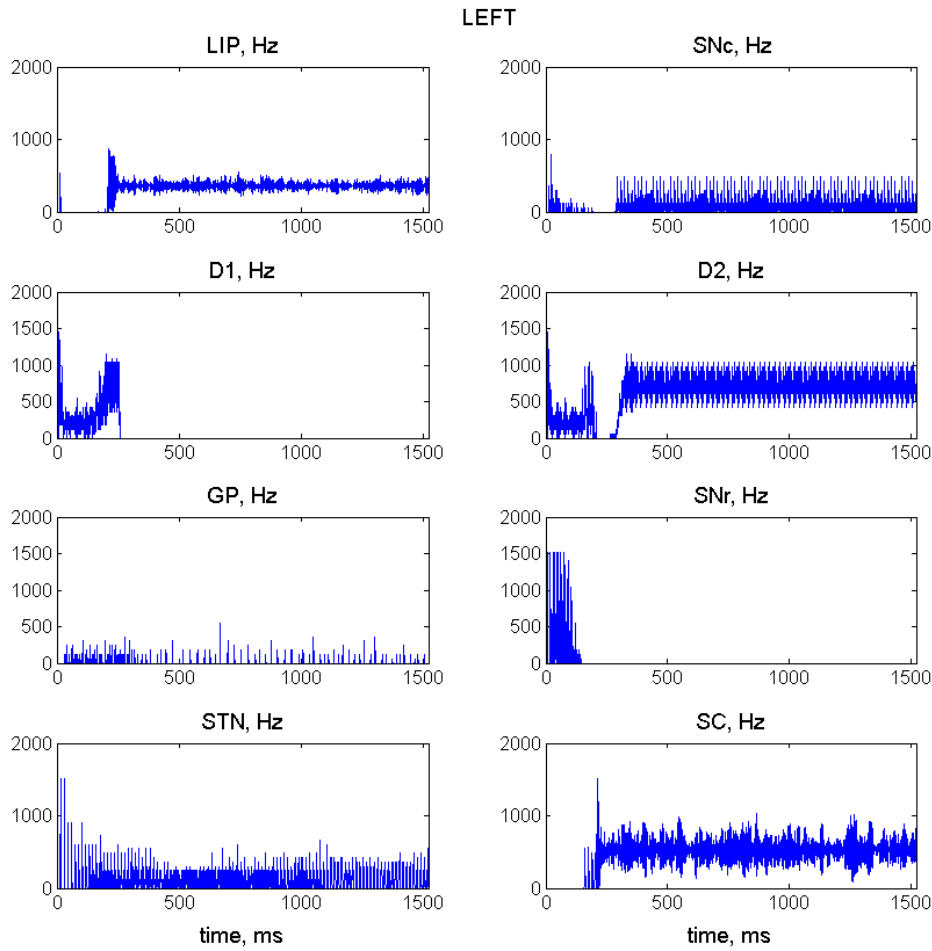
$$STDP(\Delta t) = \begin{cases} A_+ e^{-|\Delta t|/\tau_+} & \Delta t > 0 \\ A_- e^{-|\Delta t|/\tau_-} & \Delta t \leq 0 \end{cases} \quad A_+, A_- < 0$$

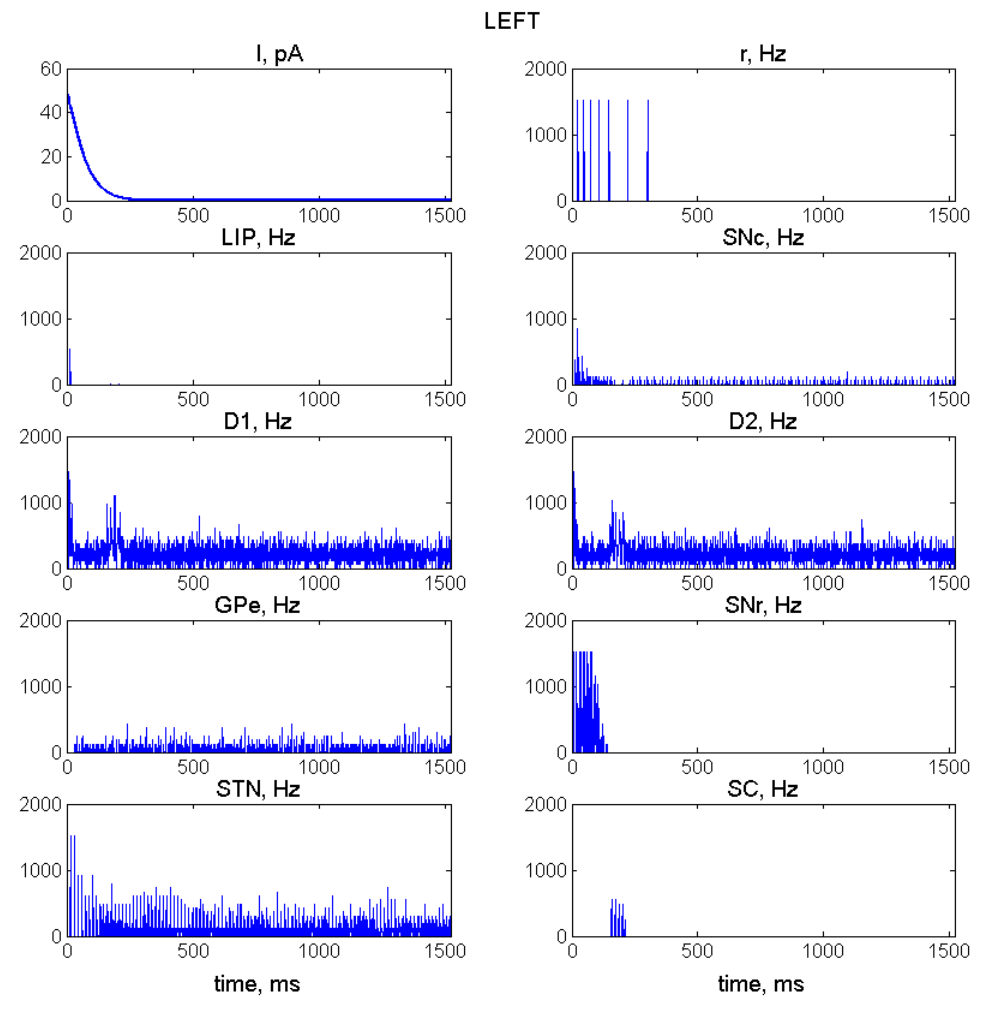
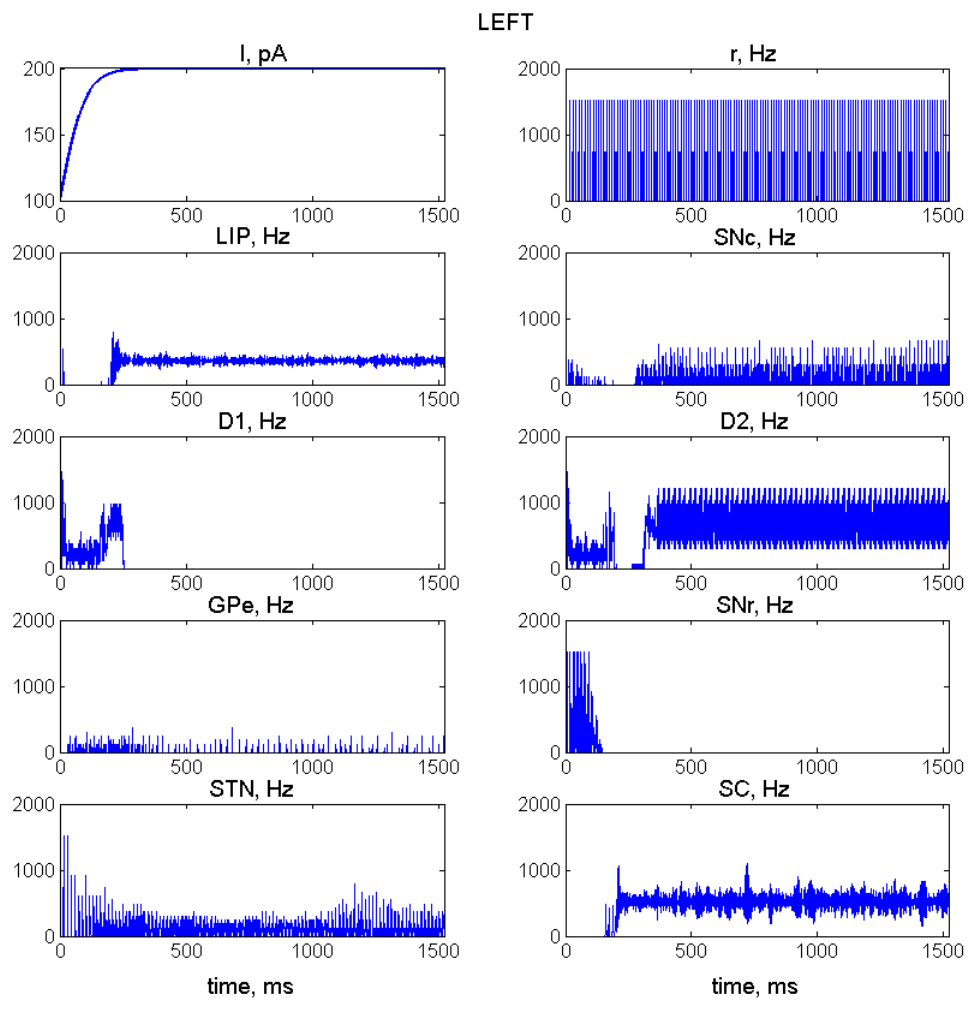
Обучение на база реакционно време

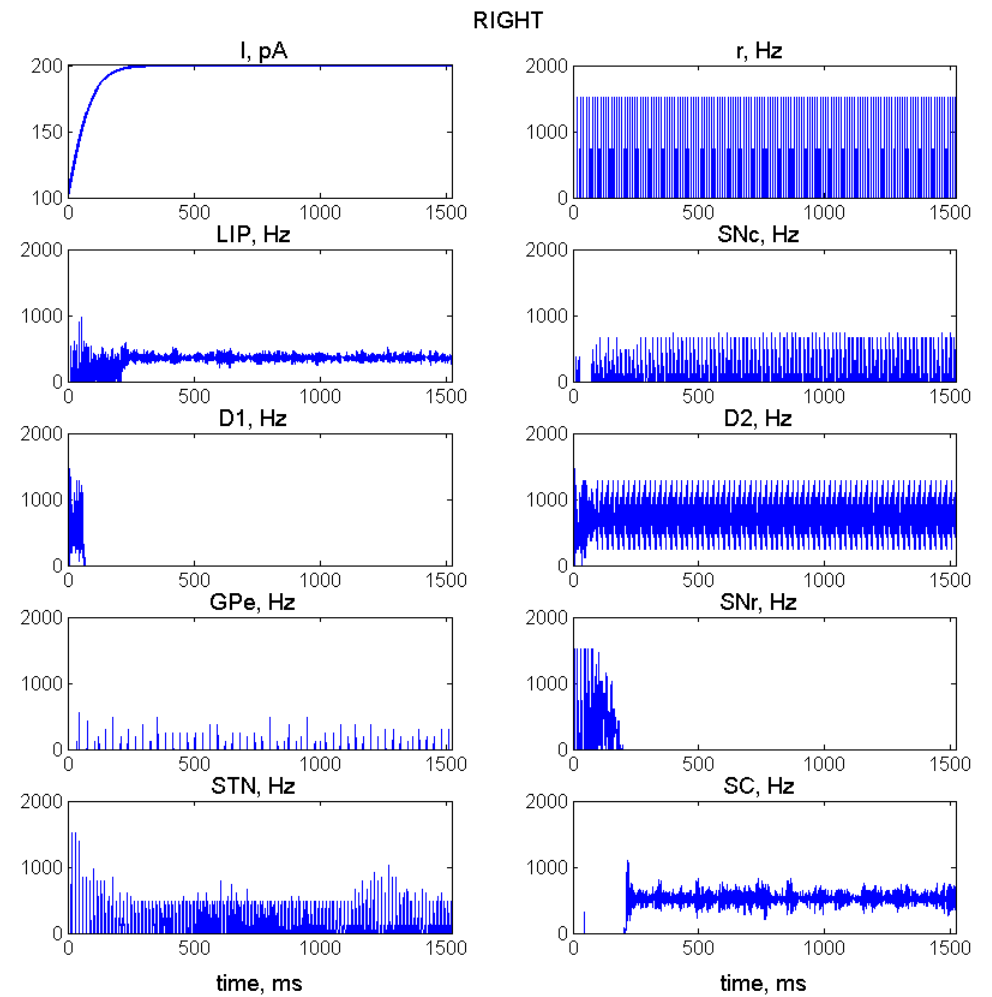
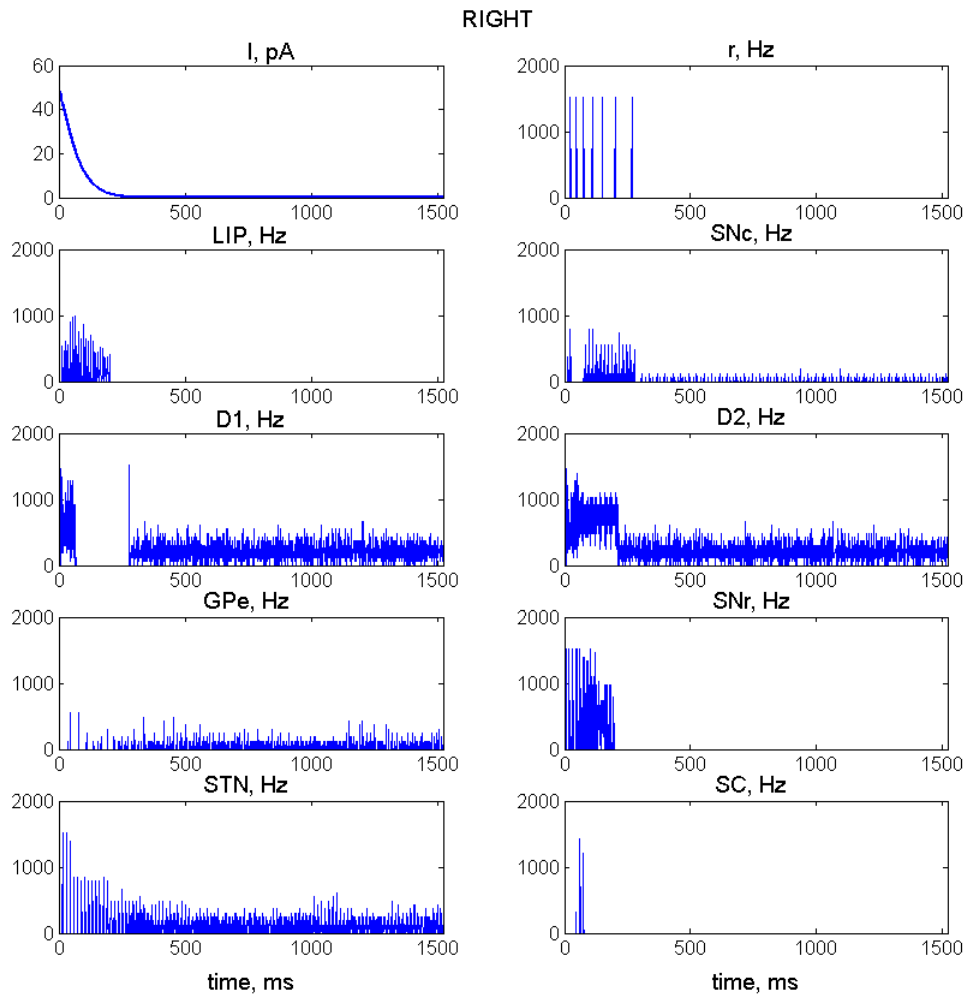


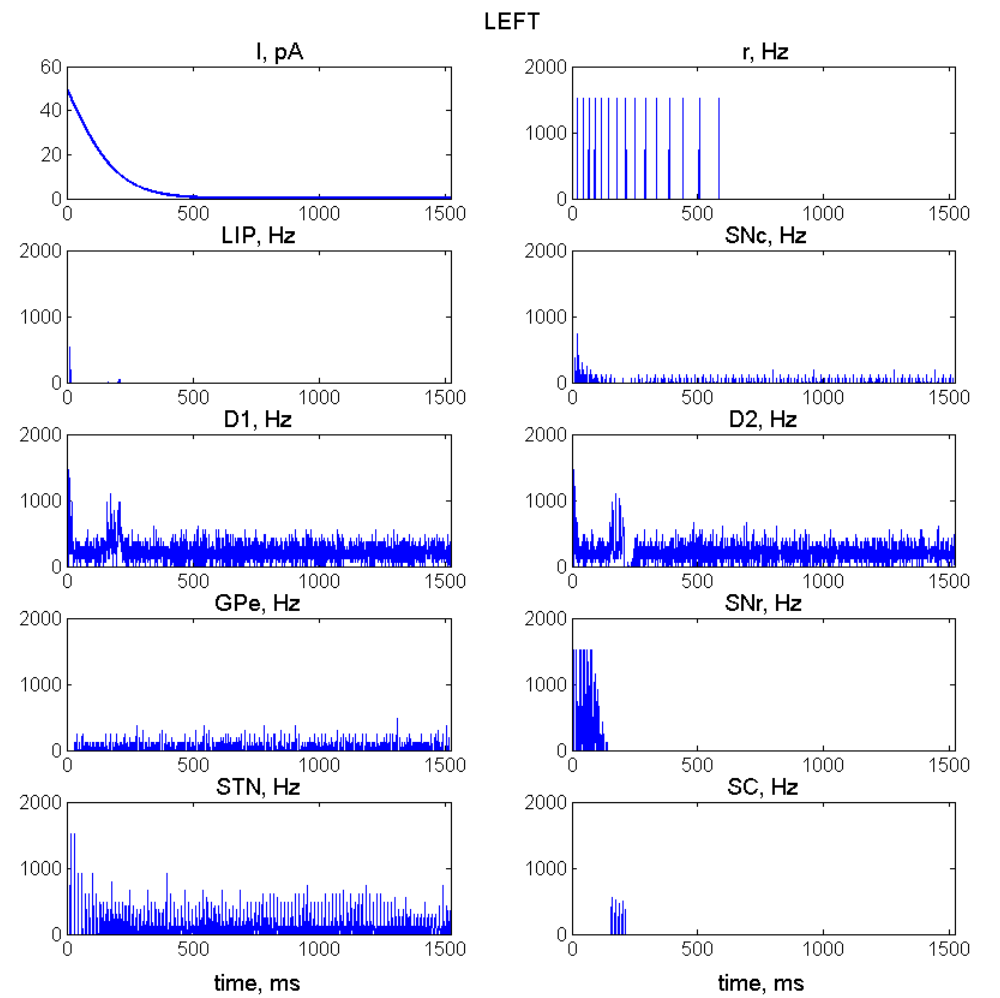
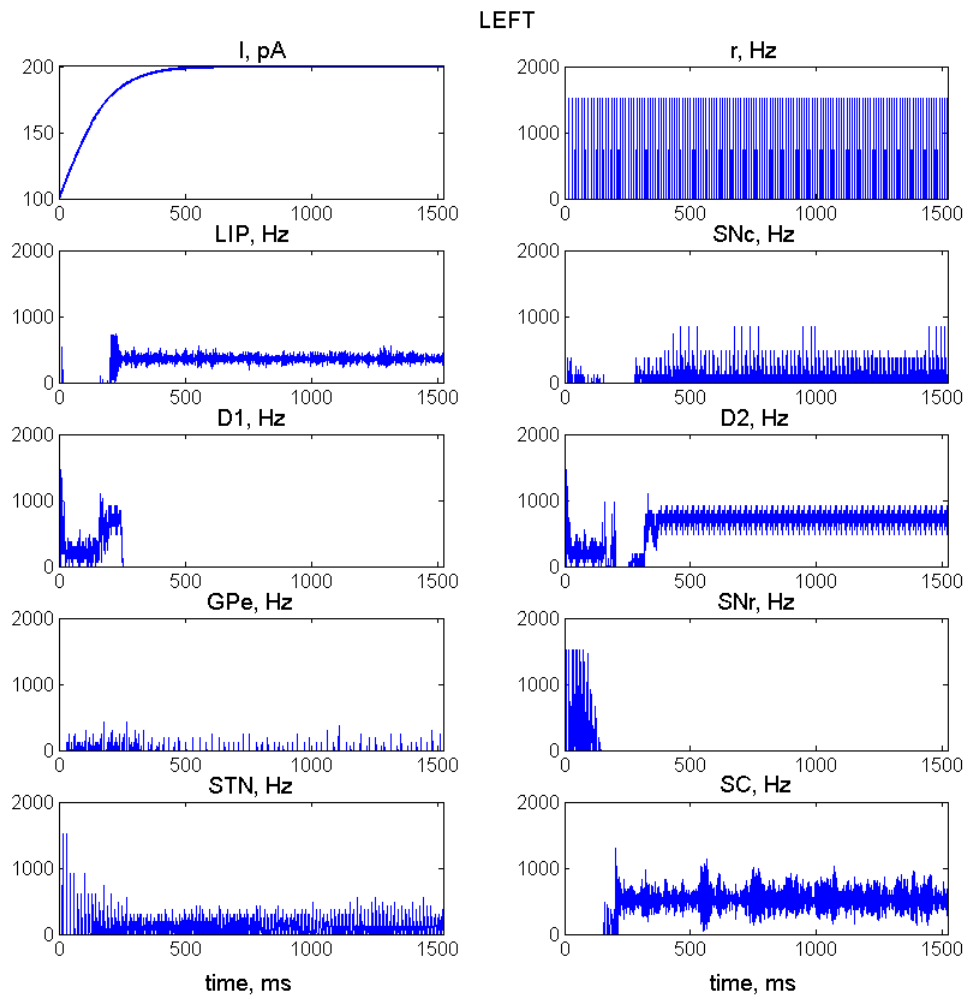
$$I_{left/right} = A_{left/right} / (1 + \exp(k_{left/right}t))$$



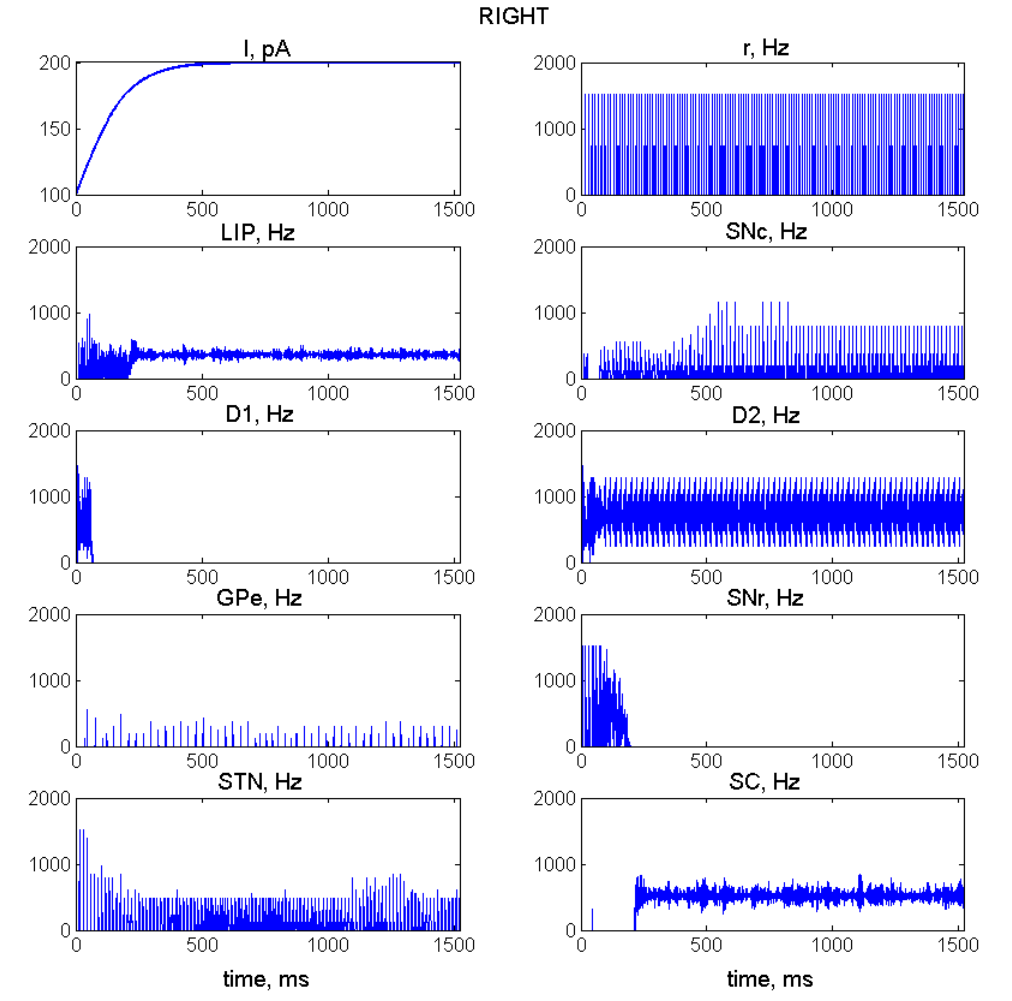
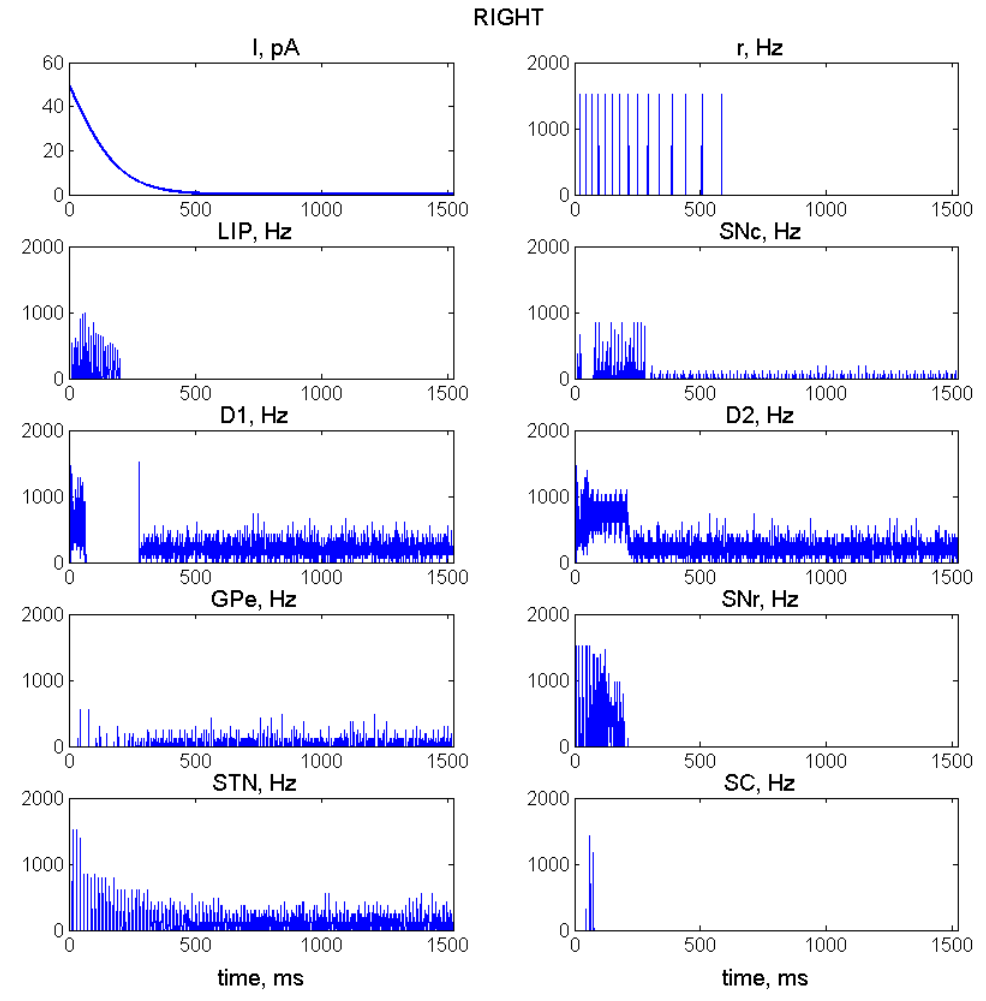


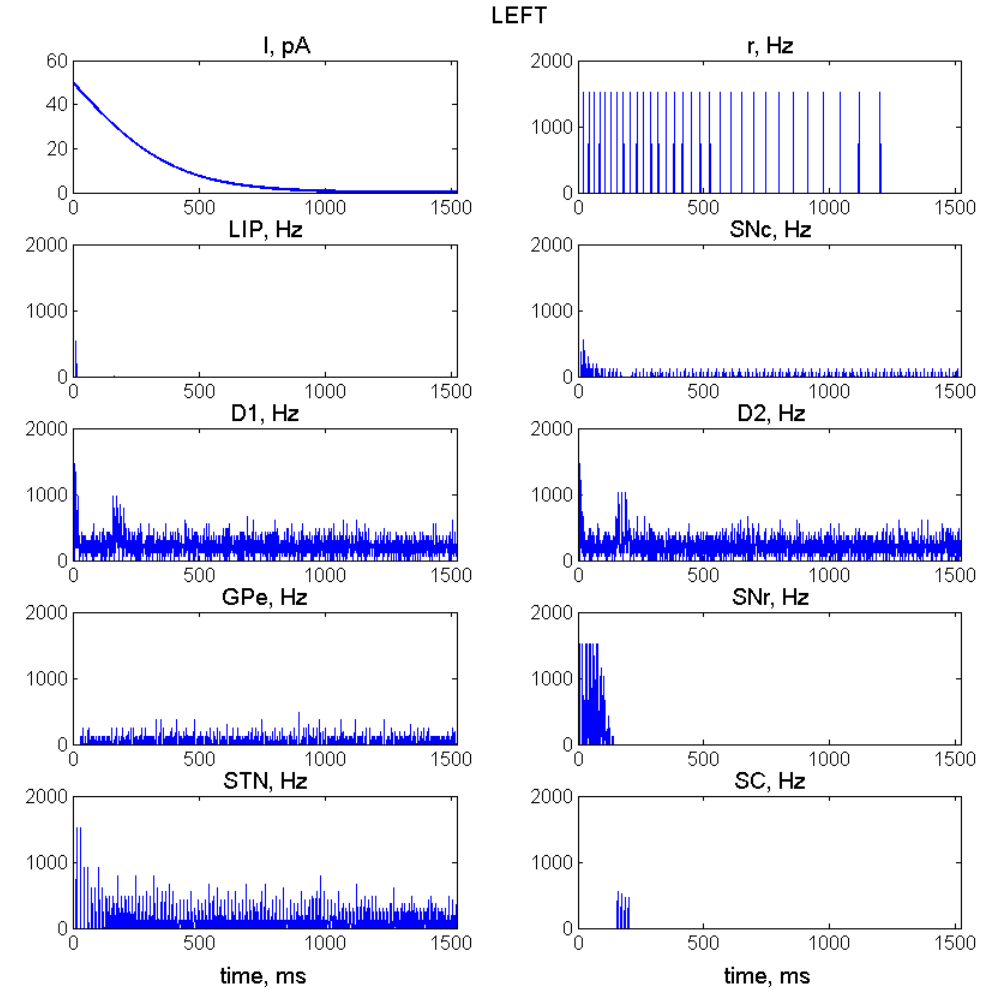
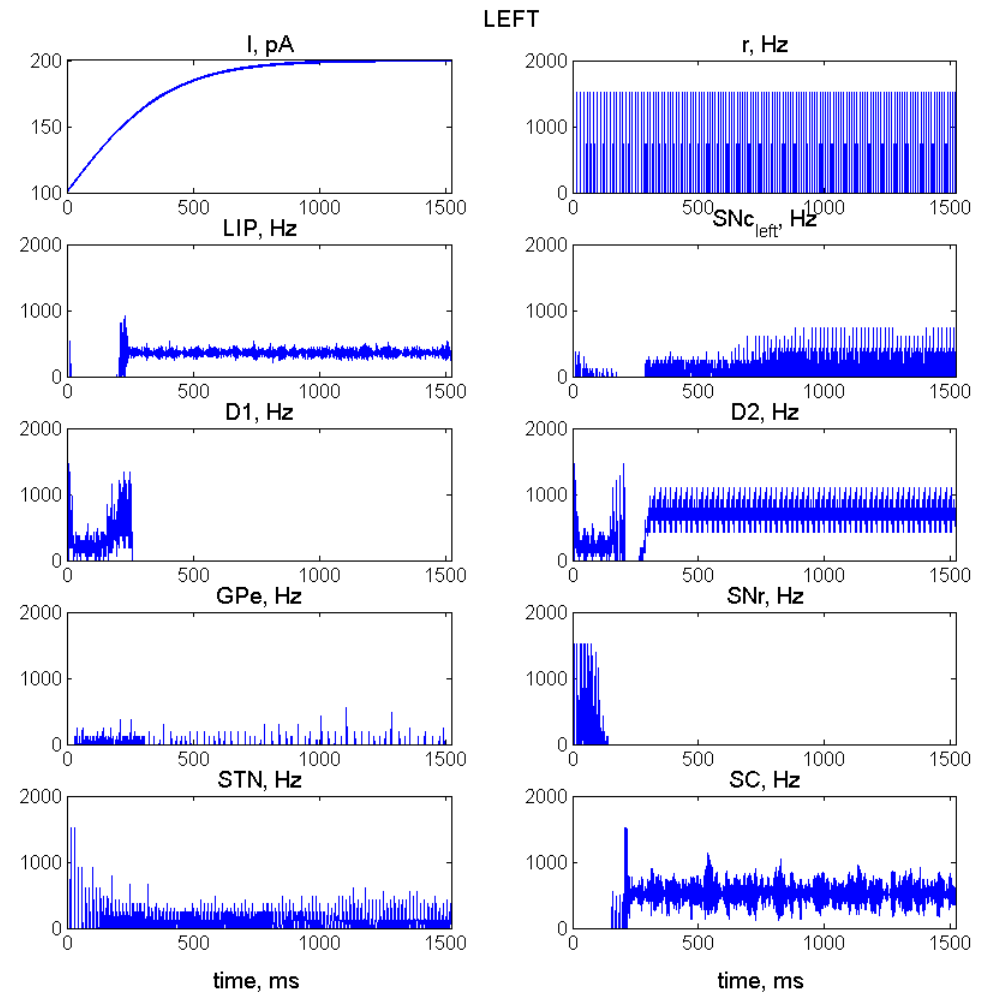


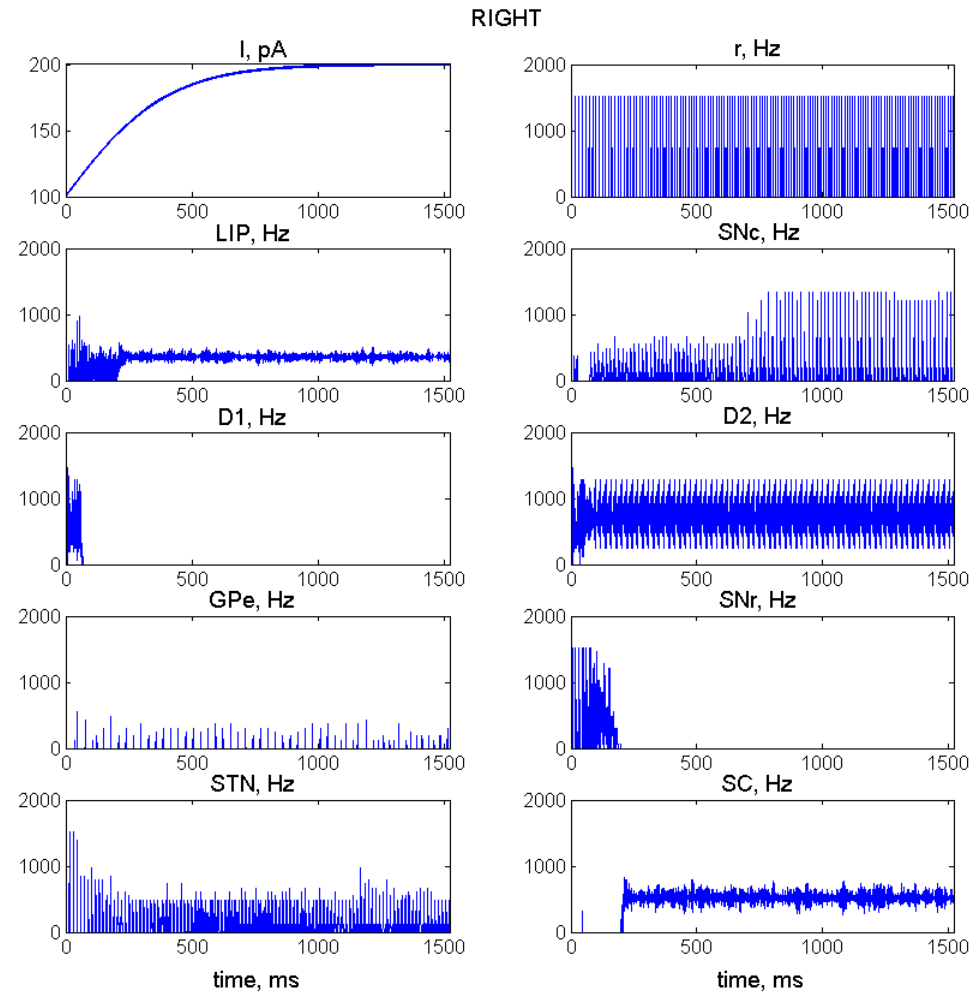
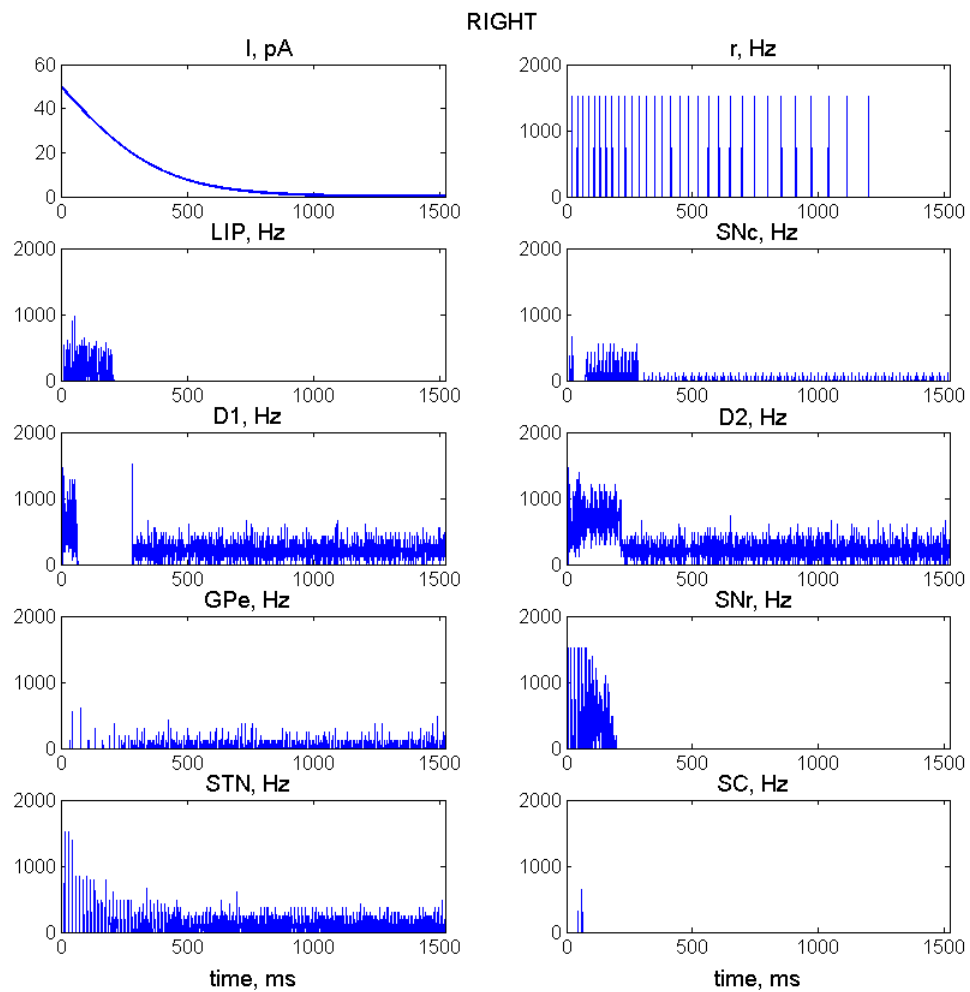




Резултати: reinforcement средна възраст, ДЯСНО

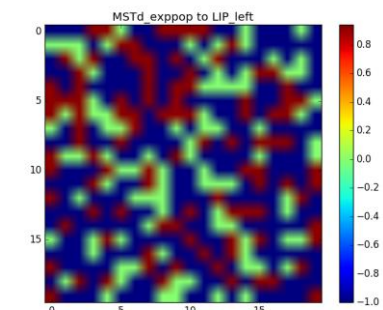
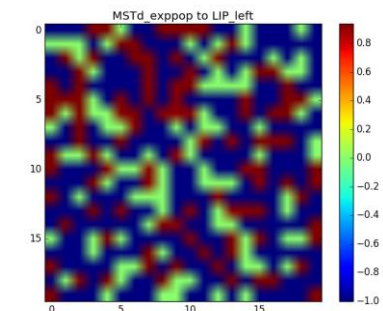
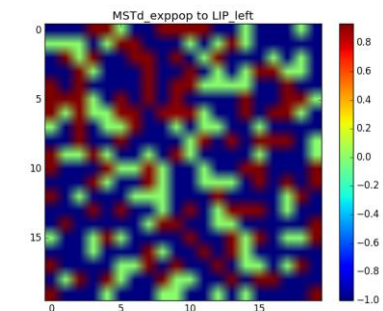
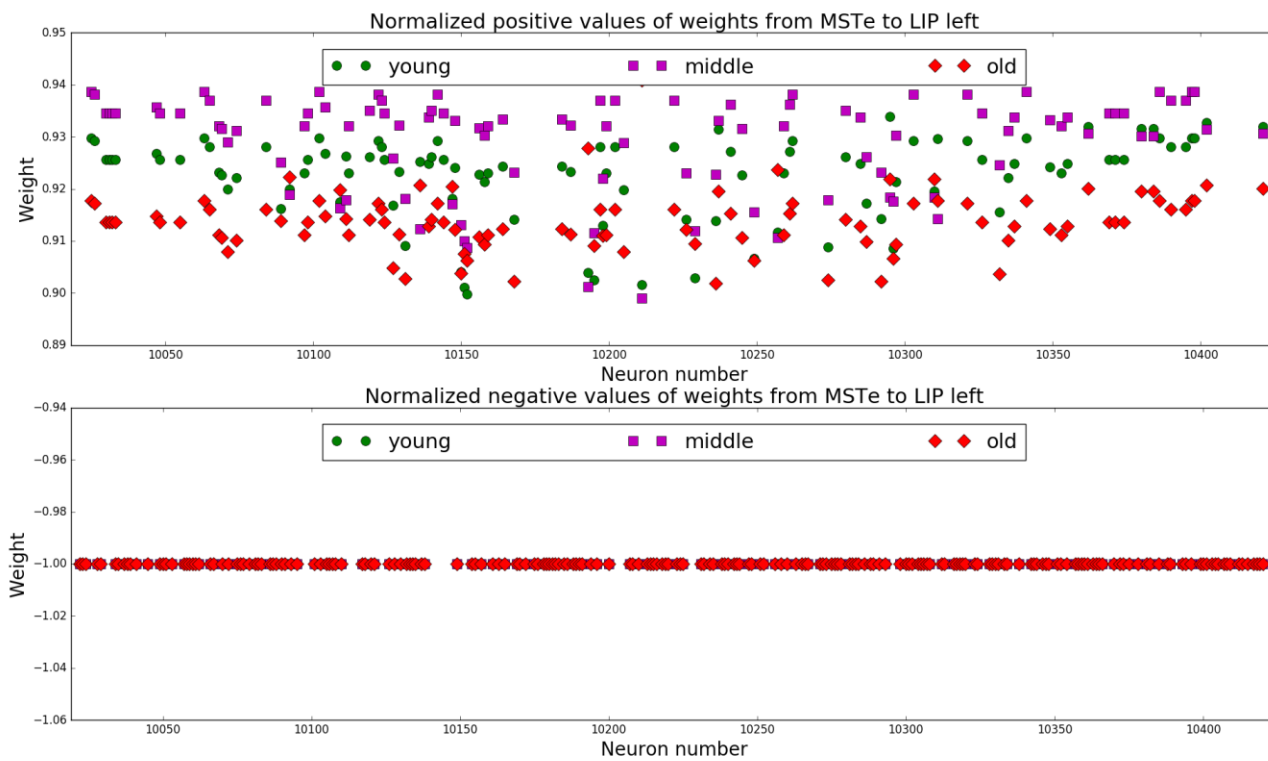




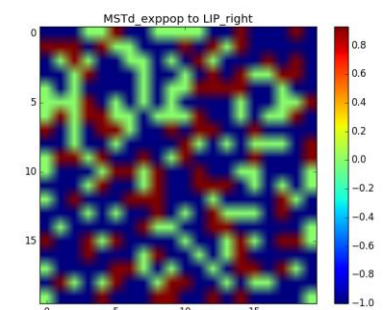
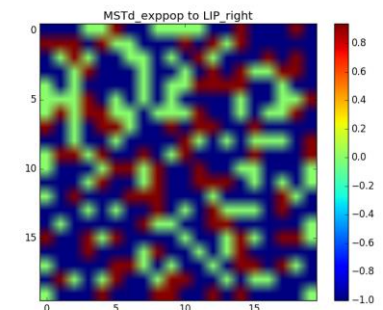
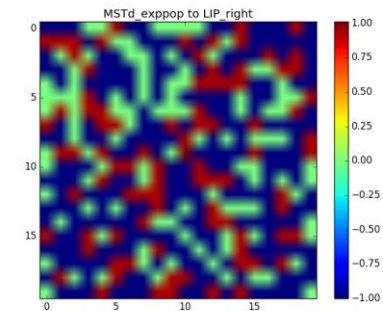
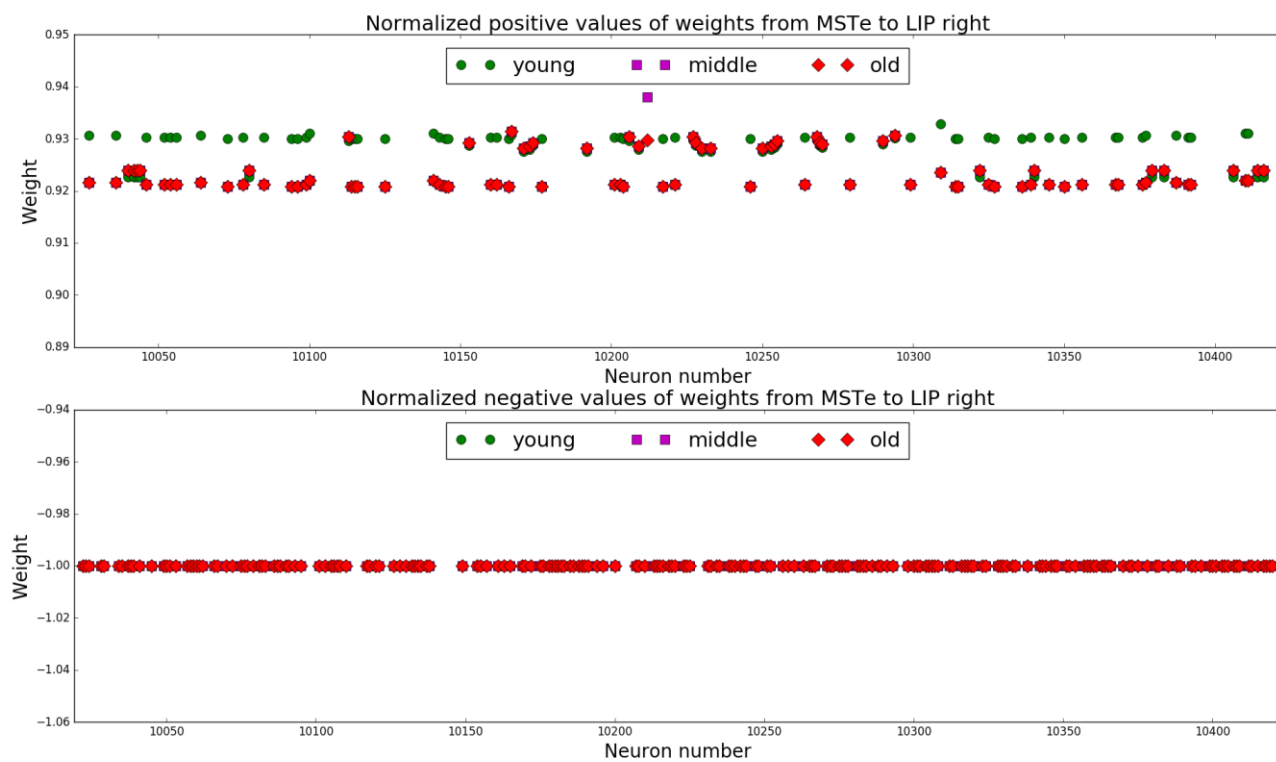


Влияние на възрастта

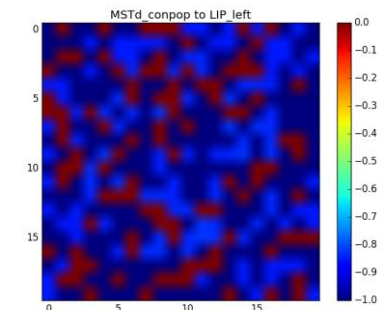
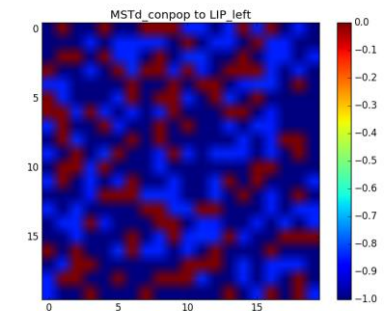
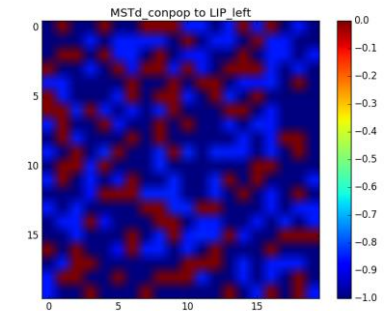
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Влияние на възрастта

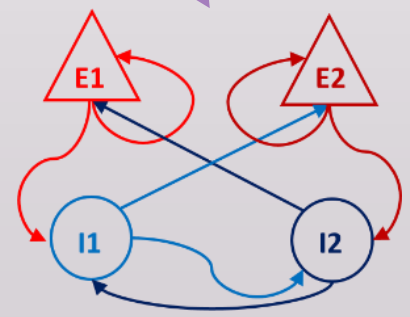
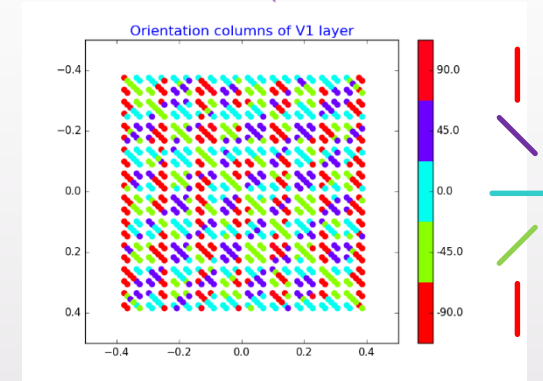
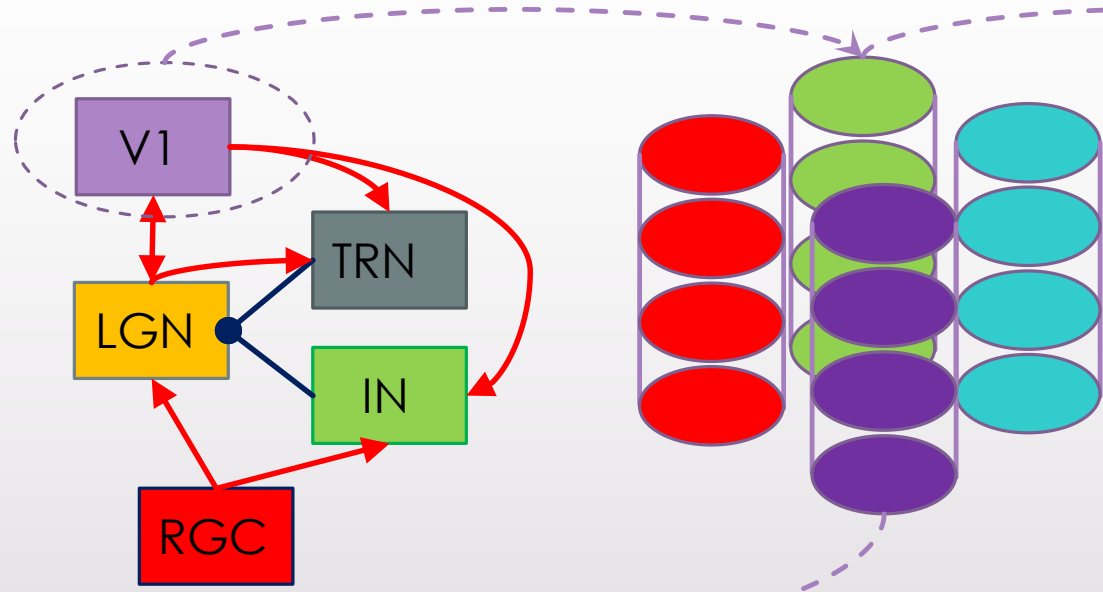


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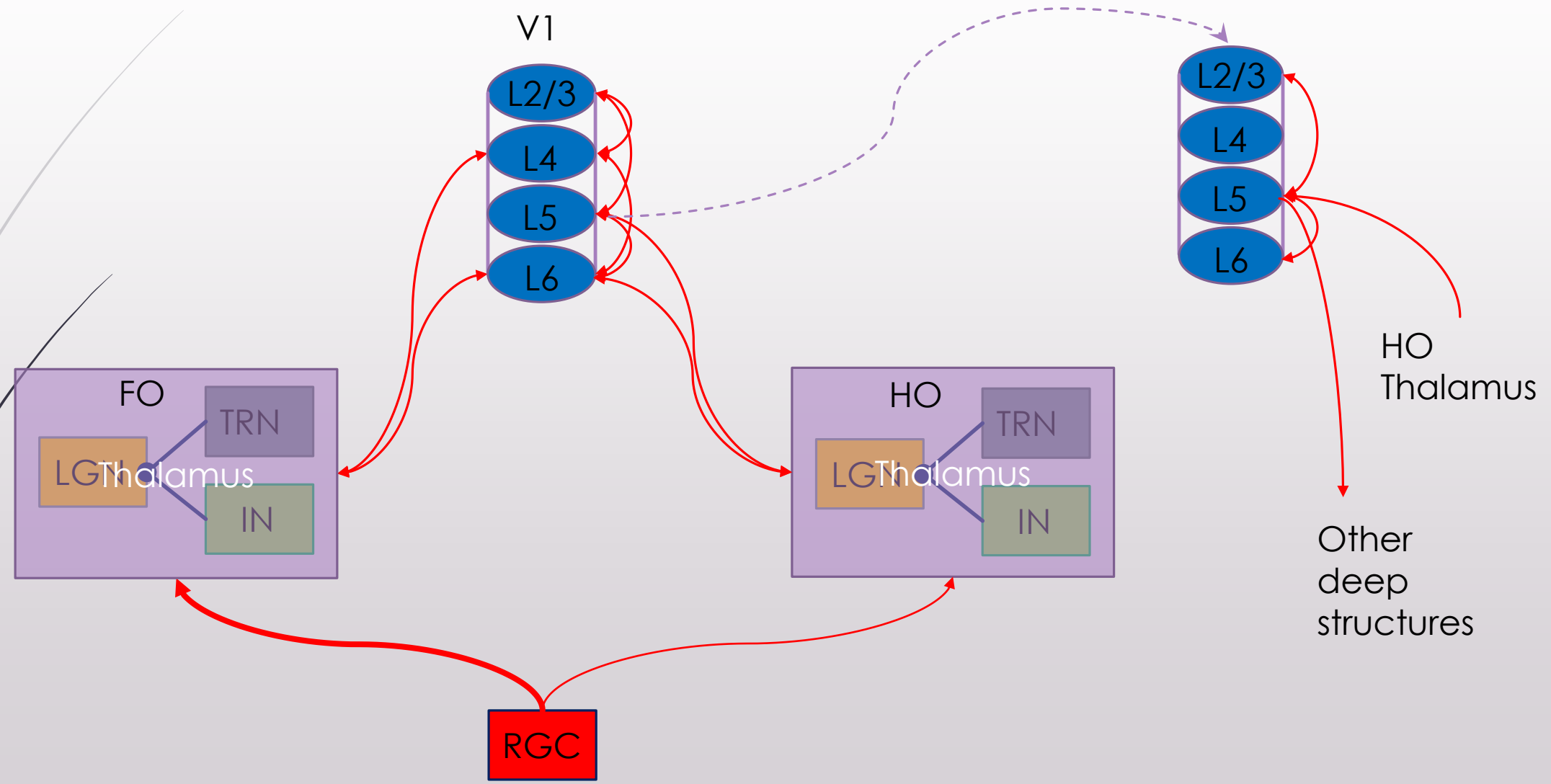


Ориентационни колони в зрителната кора – детайлна структура

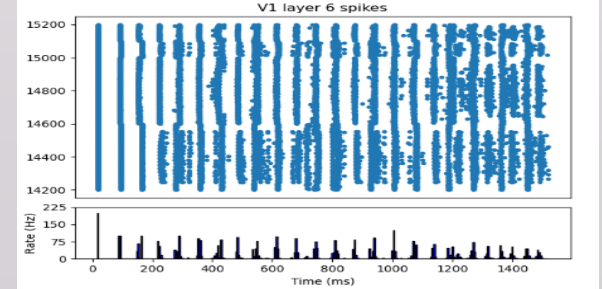
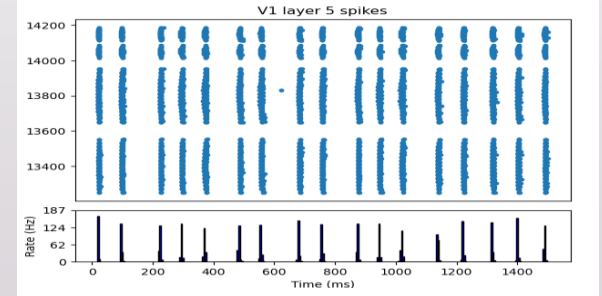
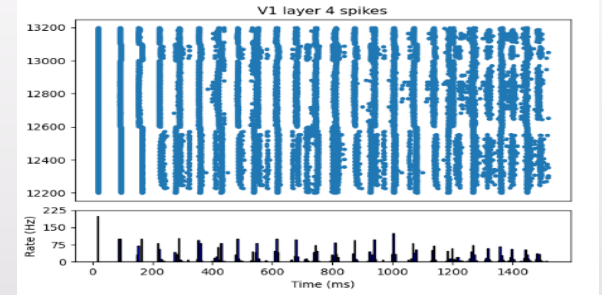
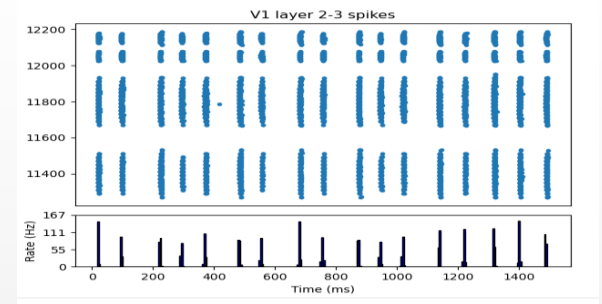
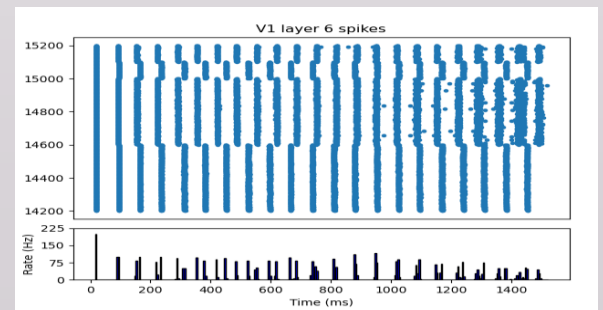
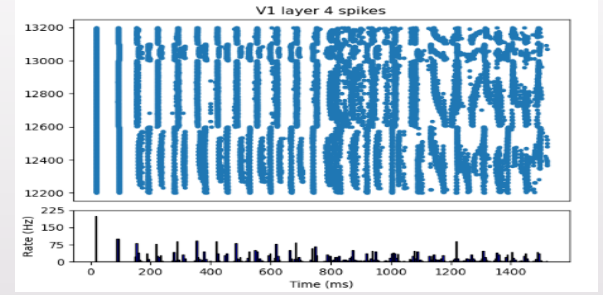
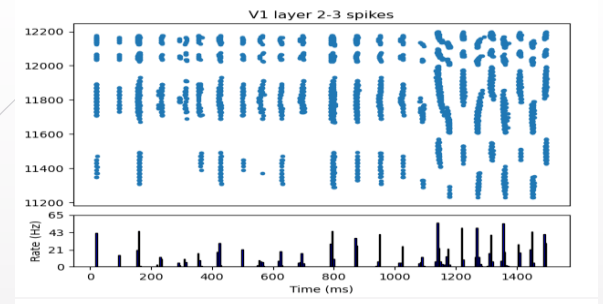
→ excitator
y
synapses
● inhibitory
synapses



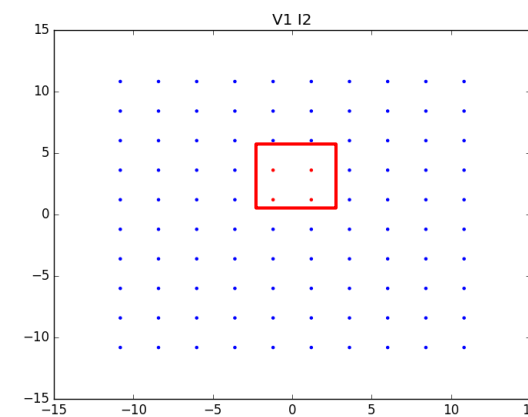
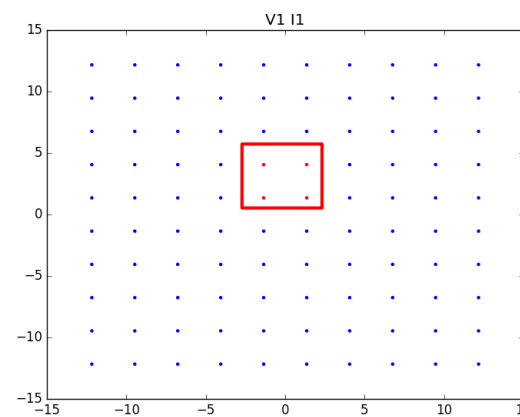
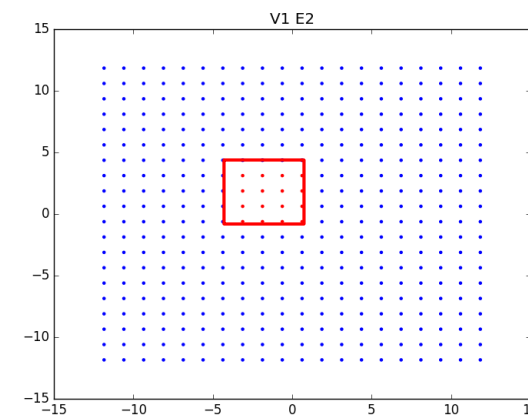
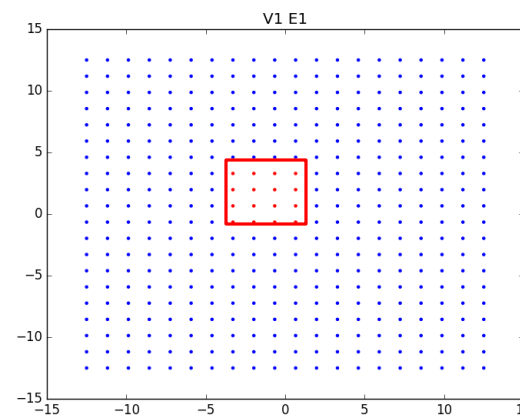
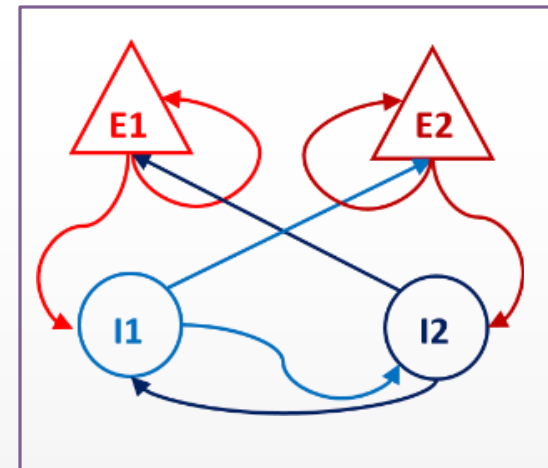
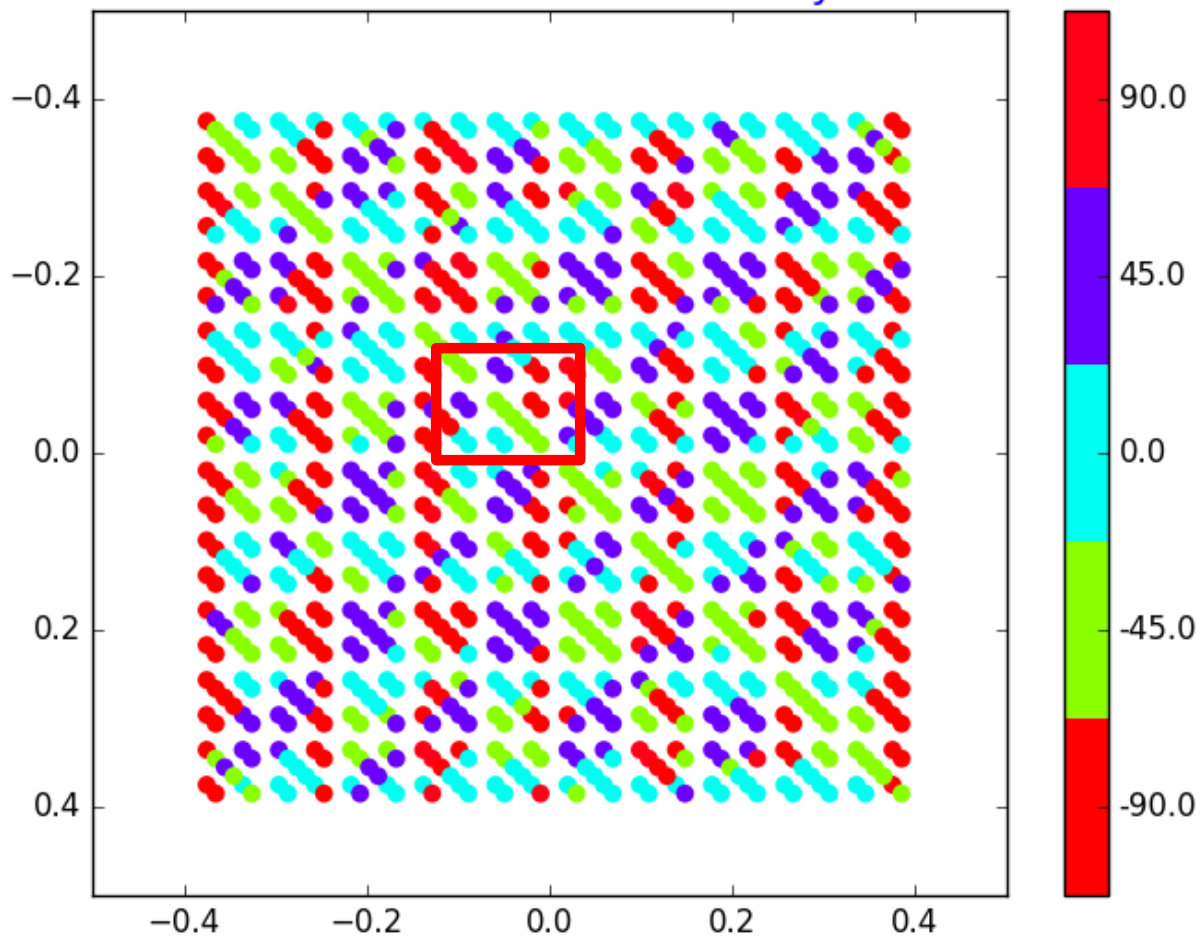
Детайлна структура на връзките между кората и таламуса

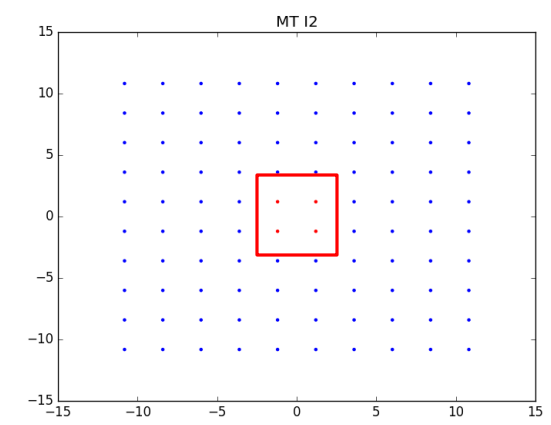
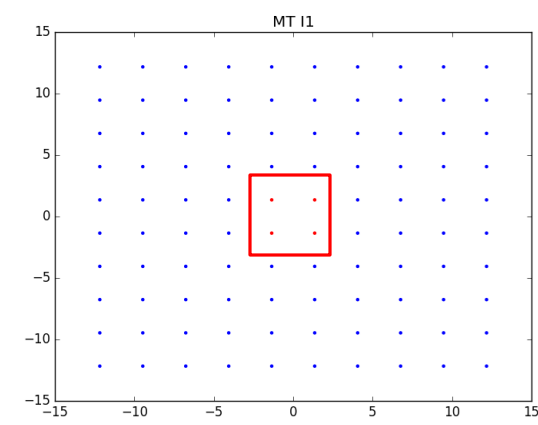
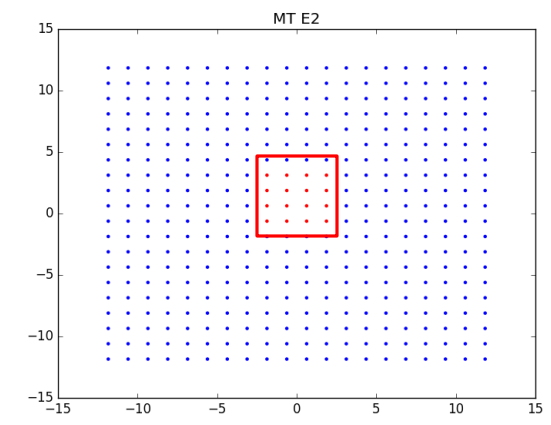
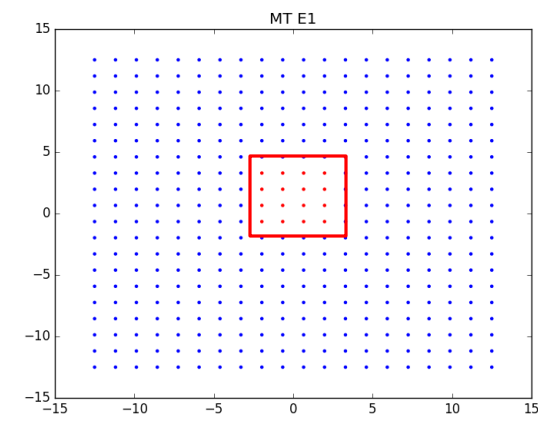
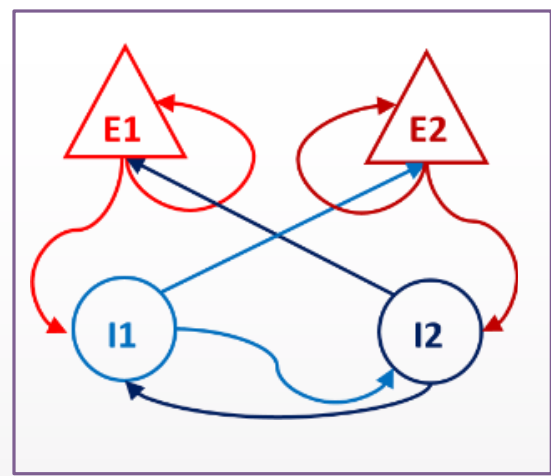
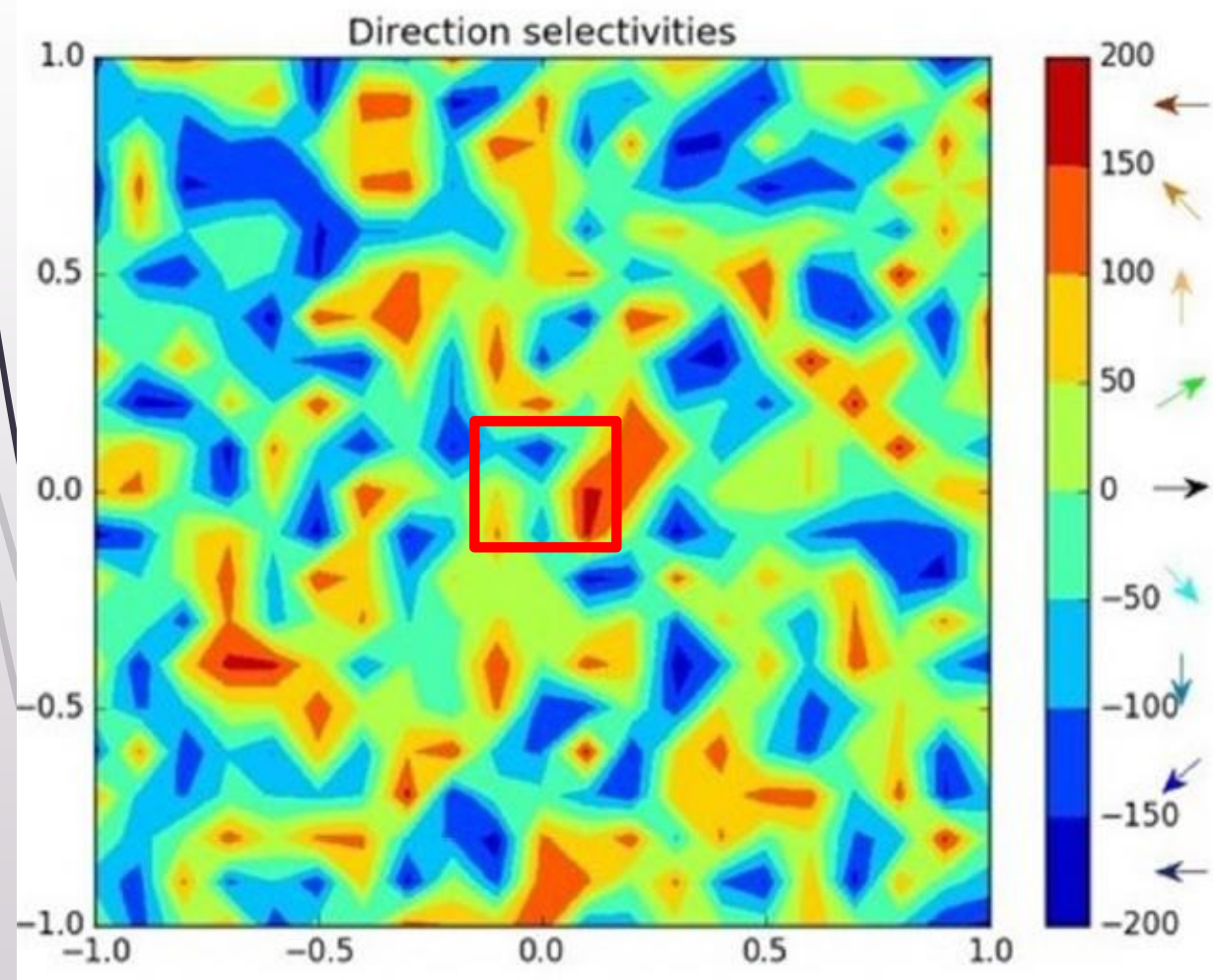


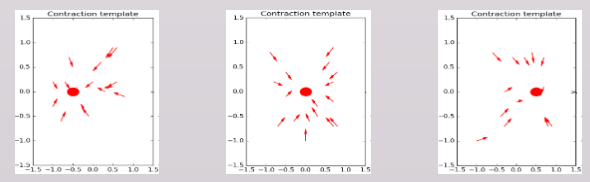
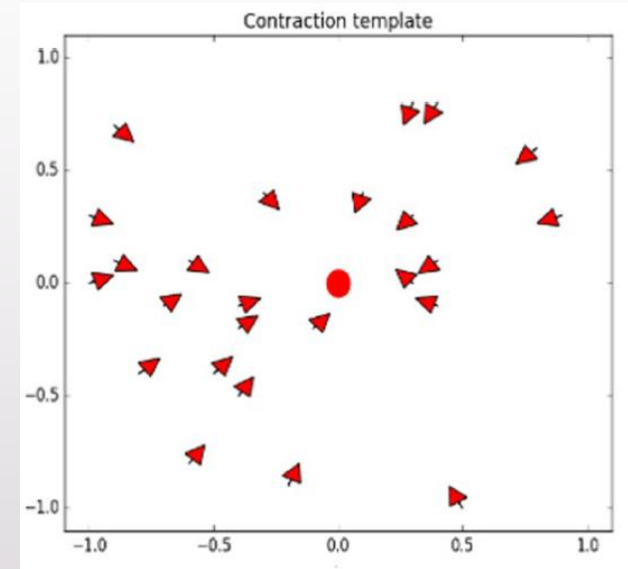
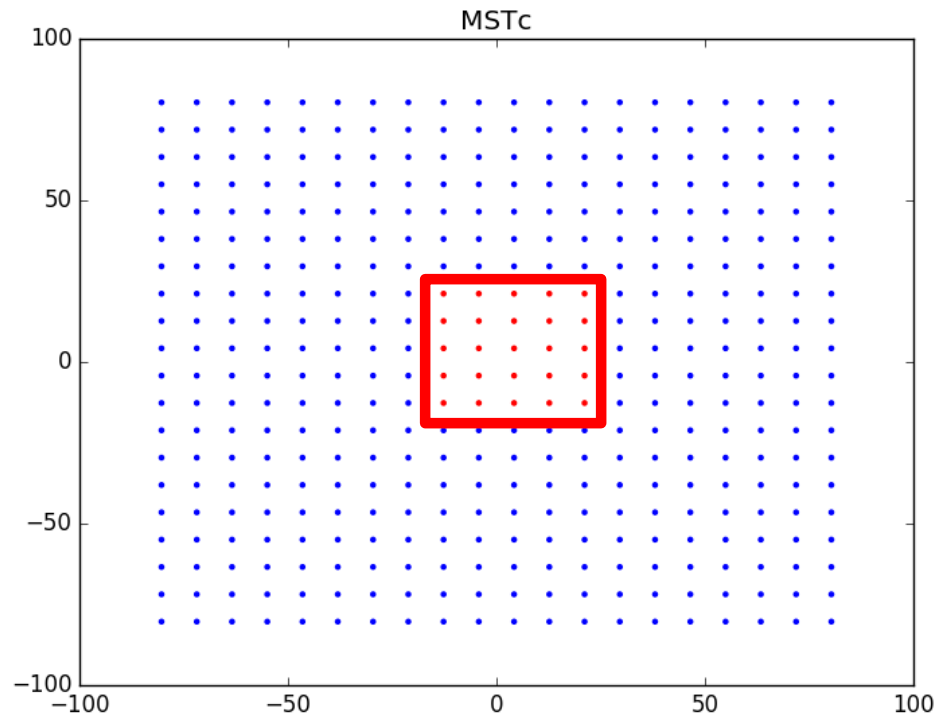
Липса (ляво) и наличие (дясно) на L5

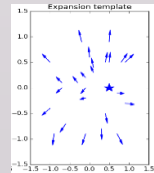
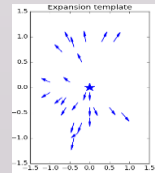
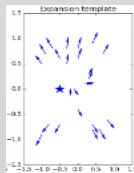
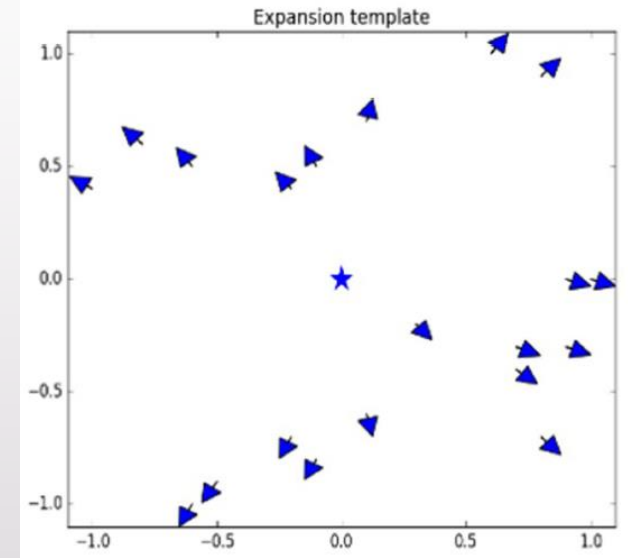
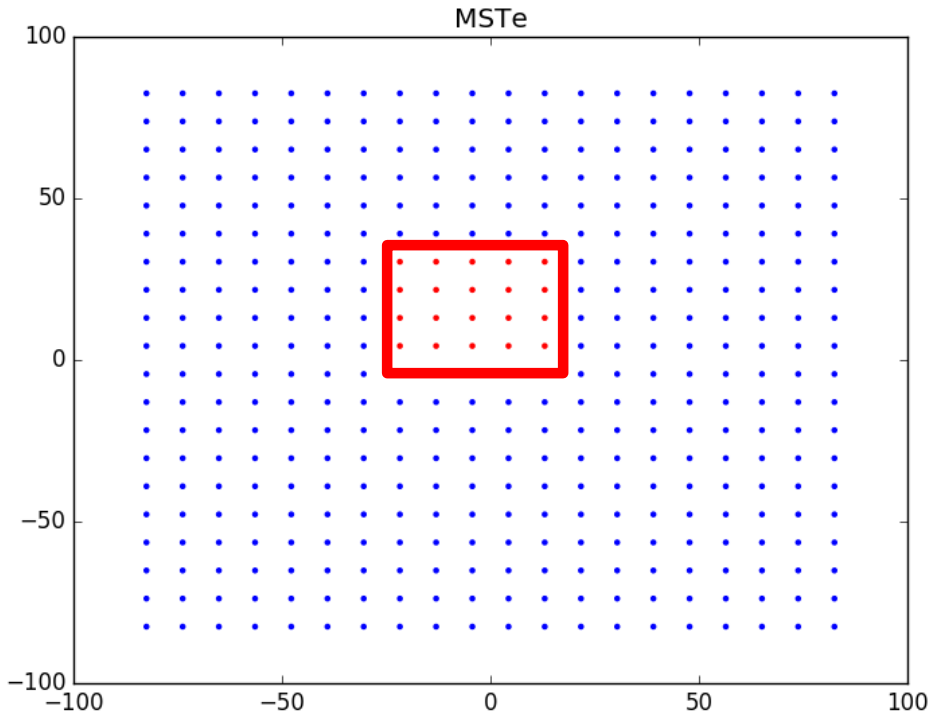


Orientation columns of V1 layer

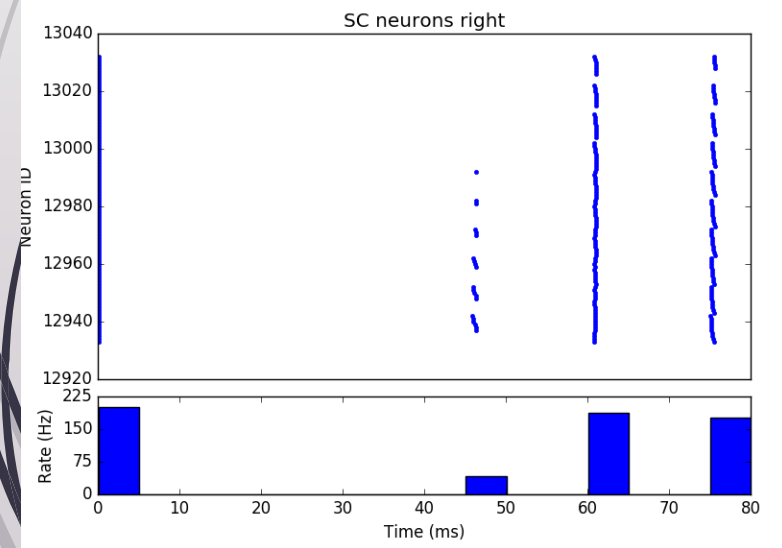
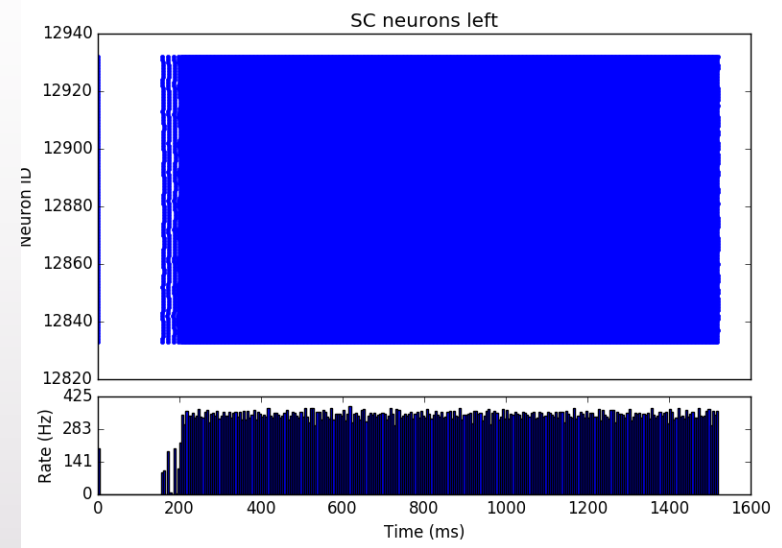




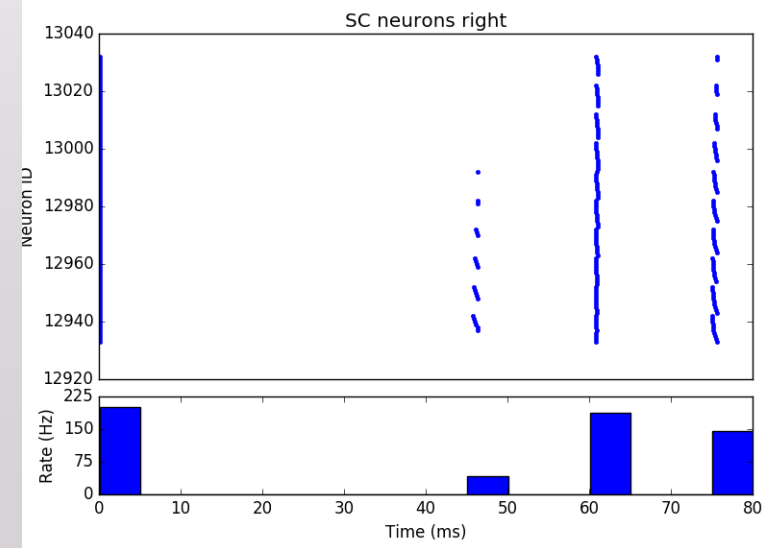
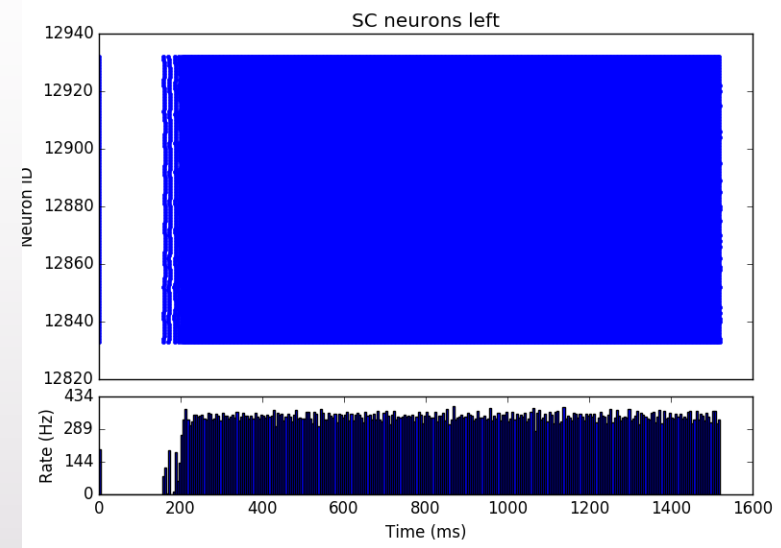




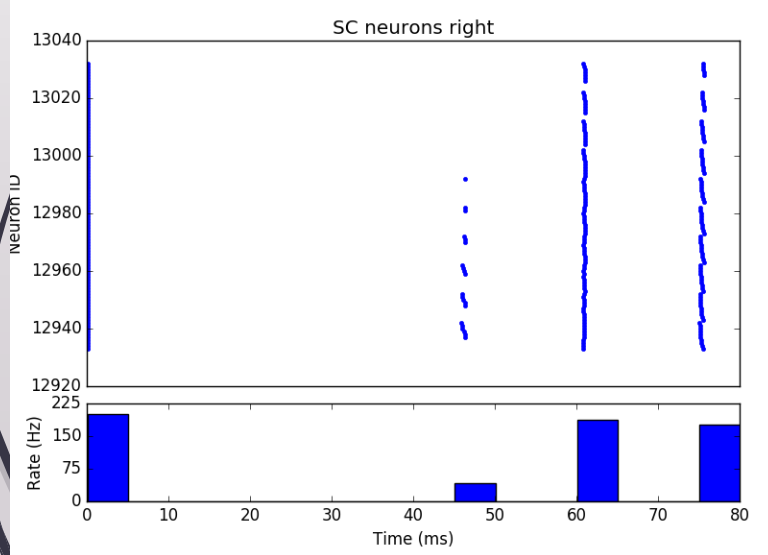
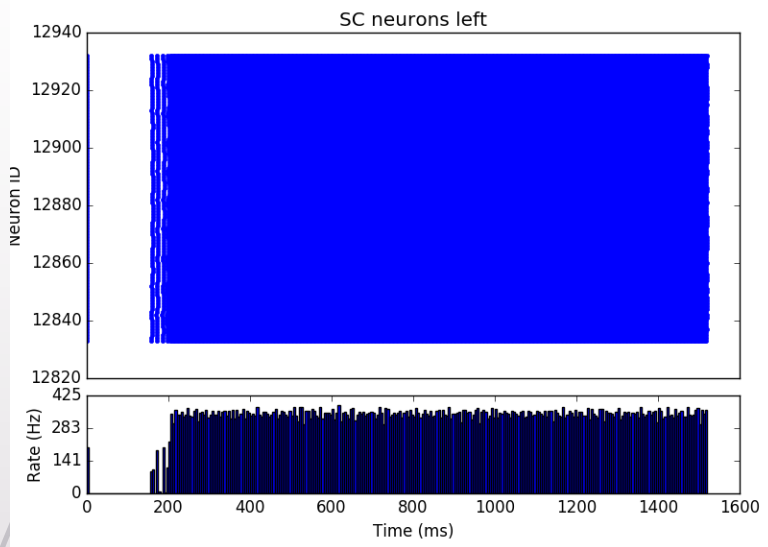
without lesion



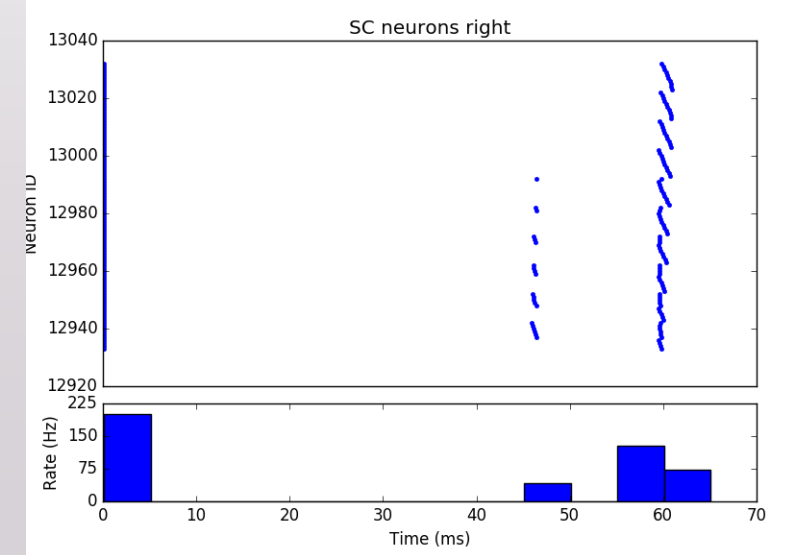
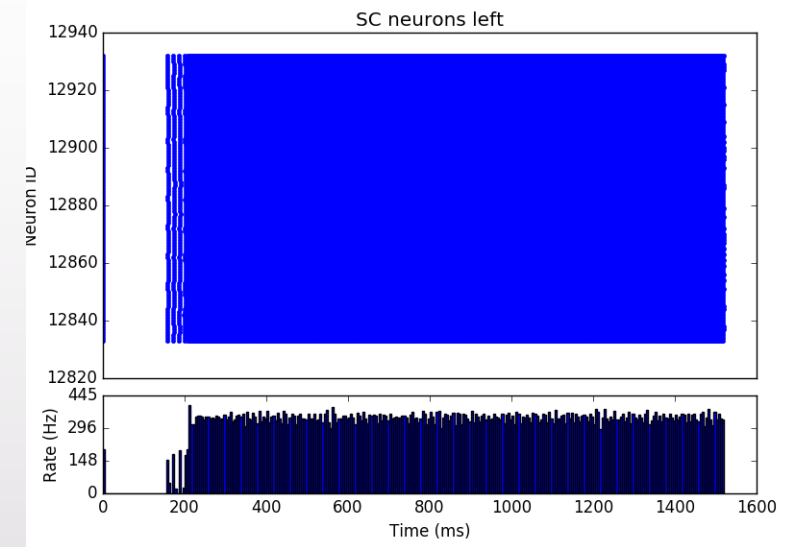
with lesion



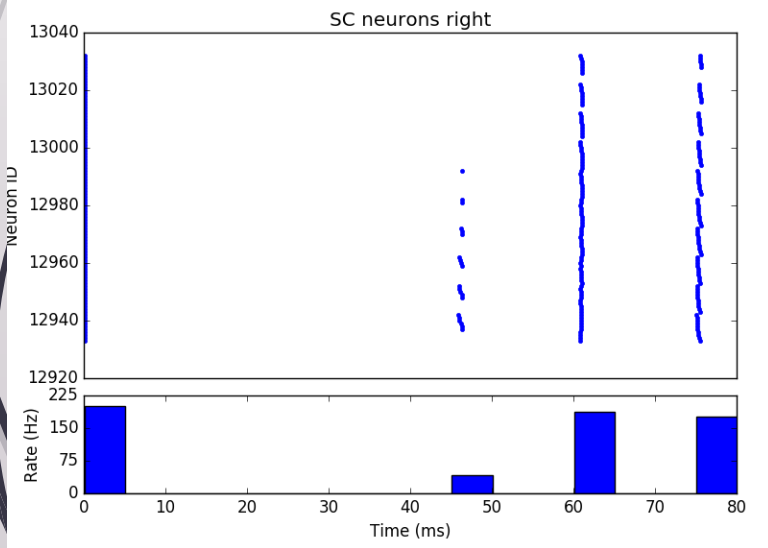
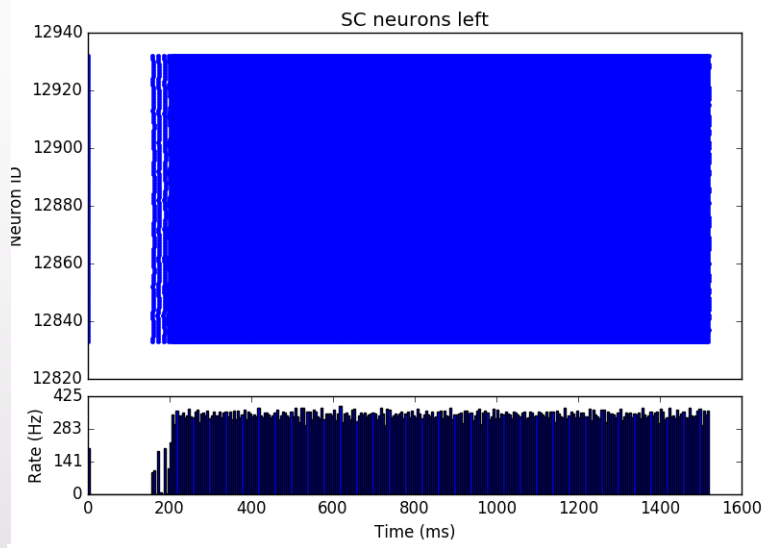
without lesion



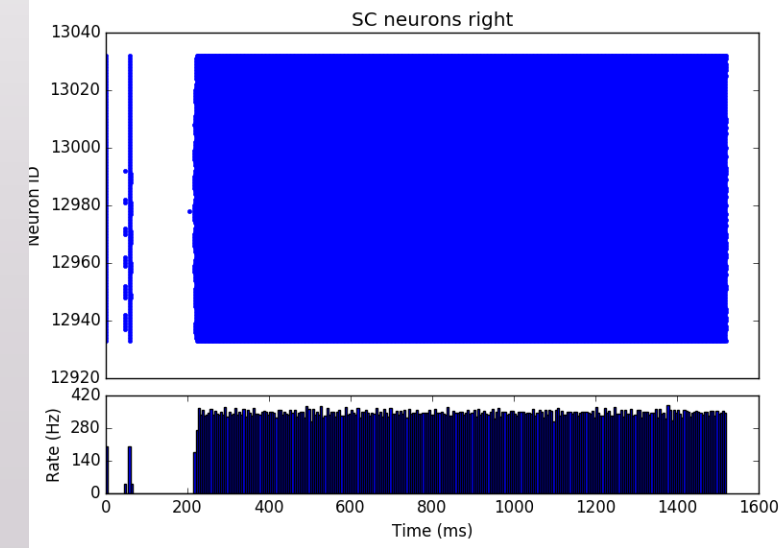
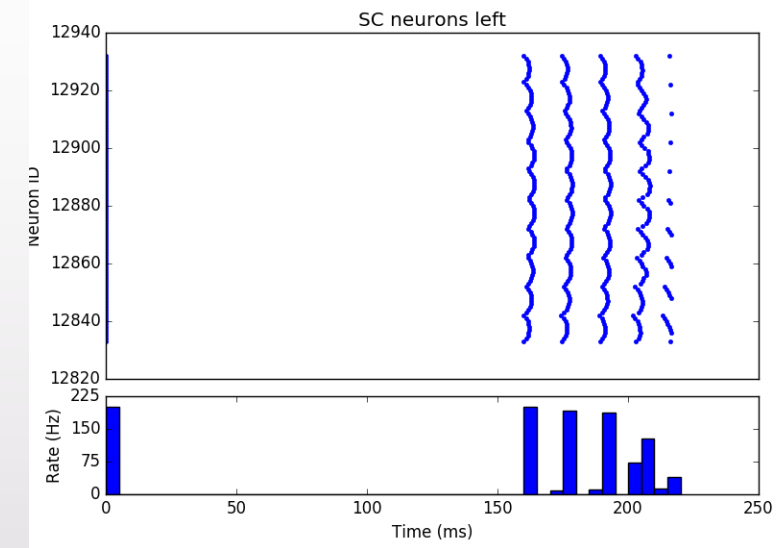
with lesion

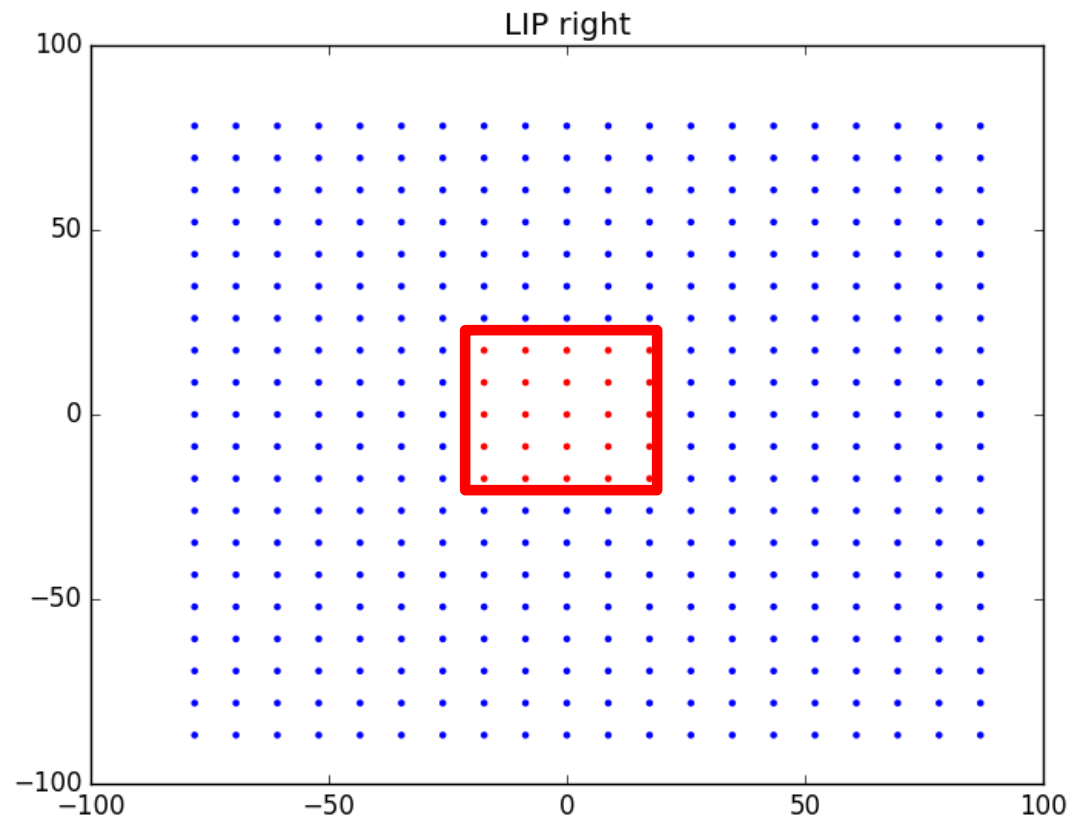
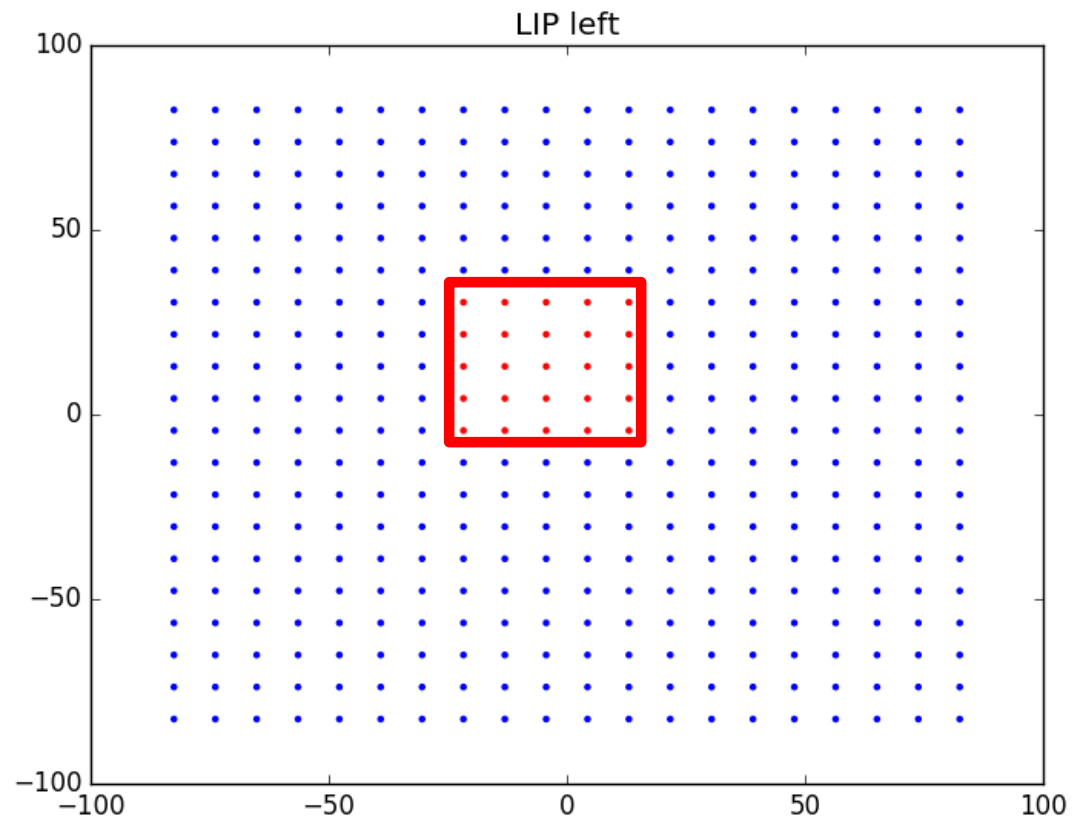


without lesion

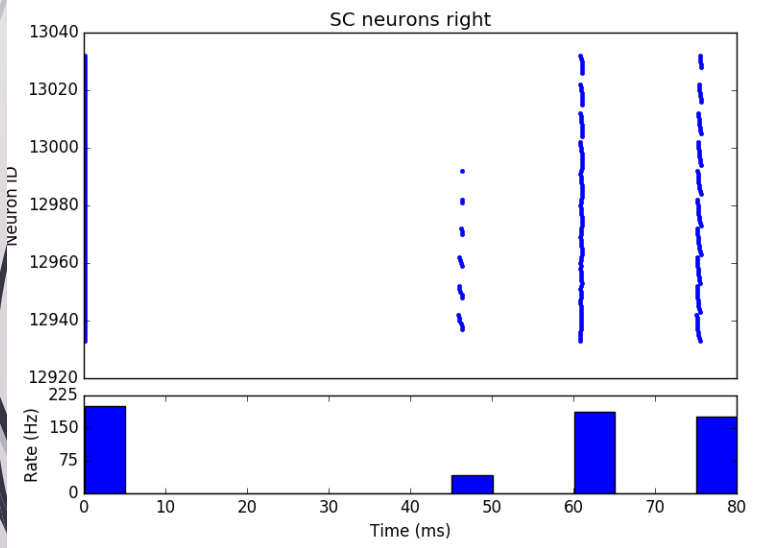
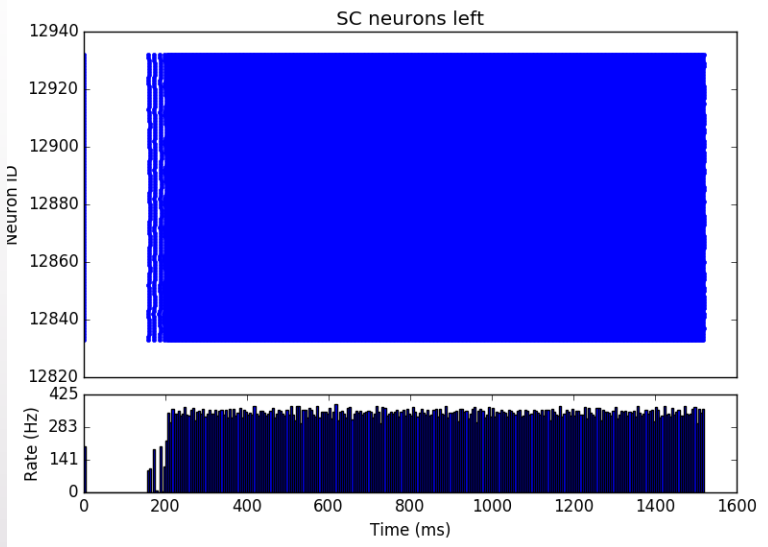


with lesion

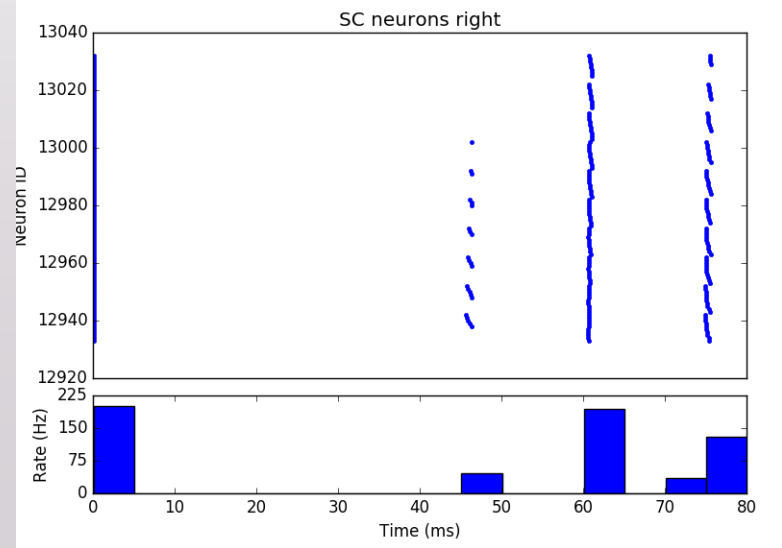
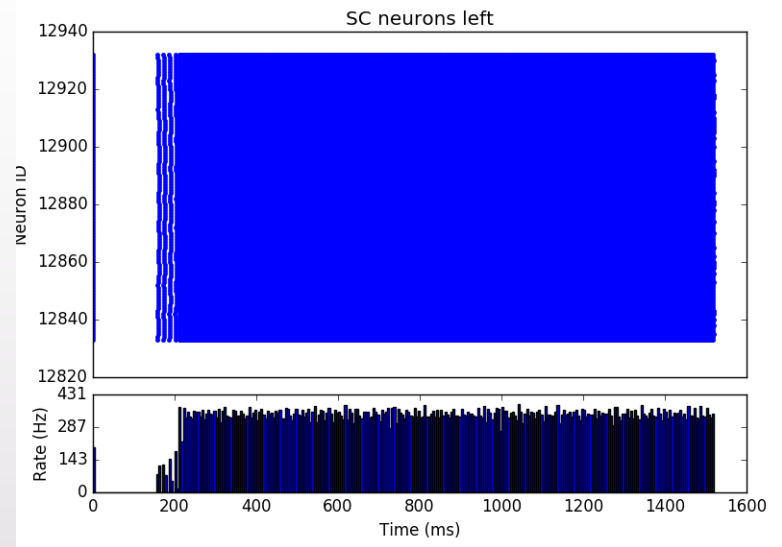




without lesion

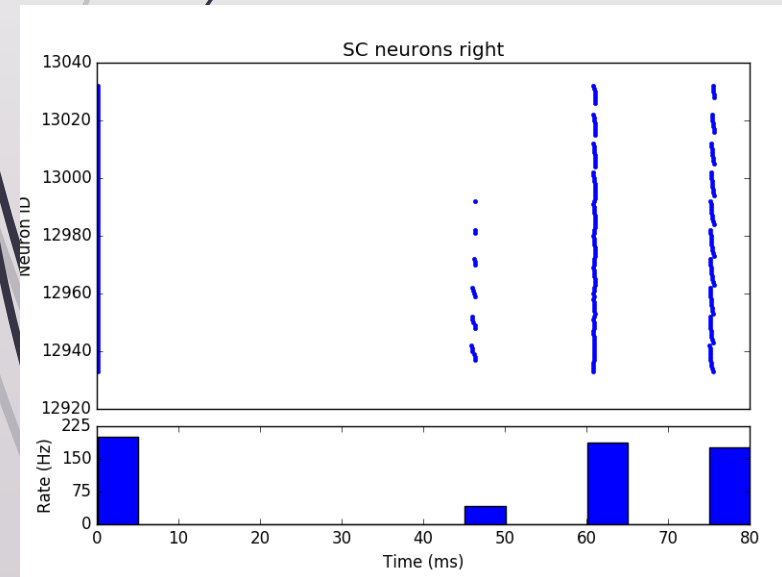
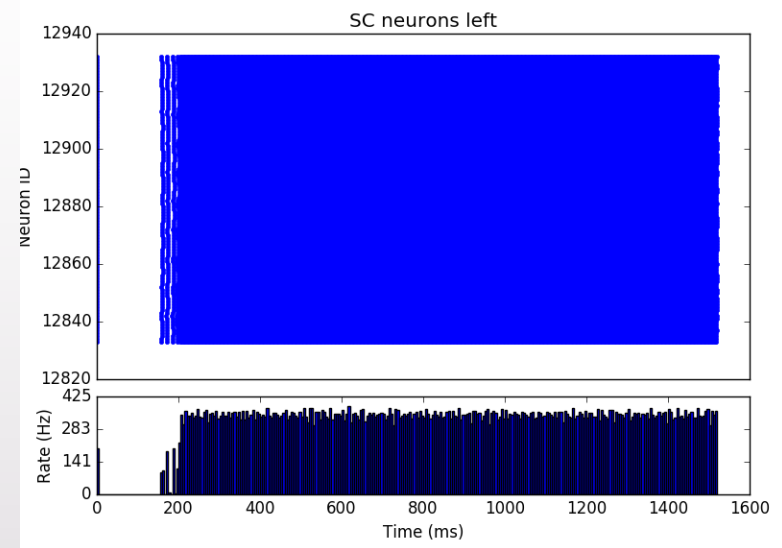


with lesion

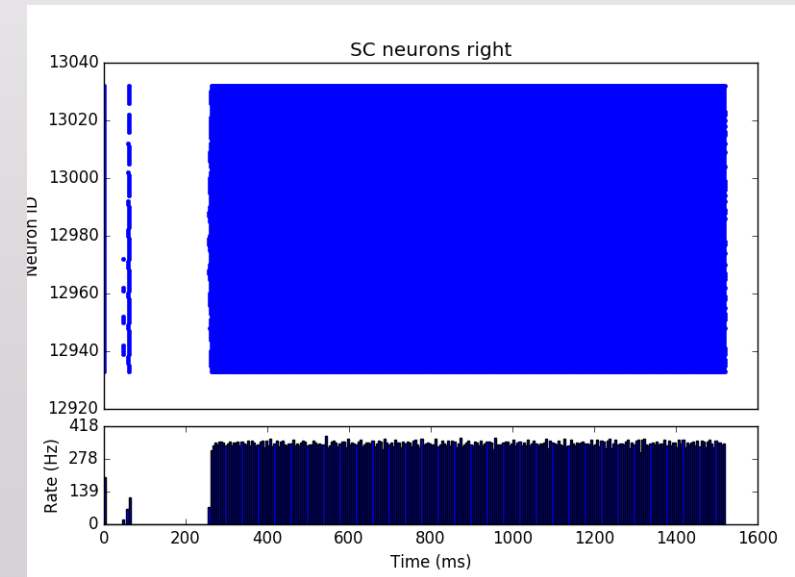
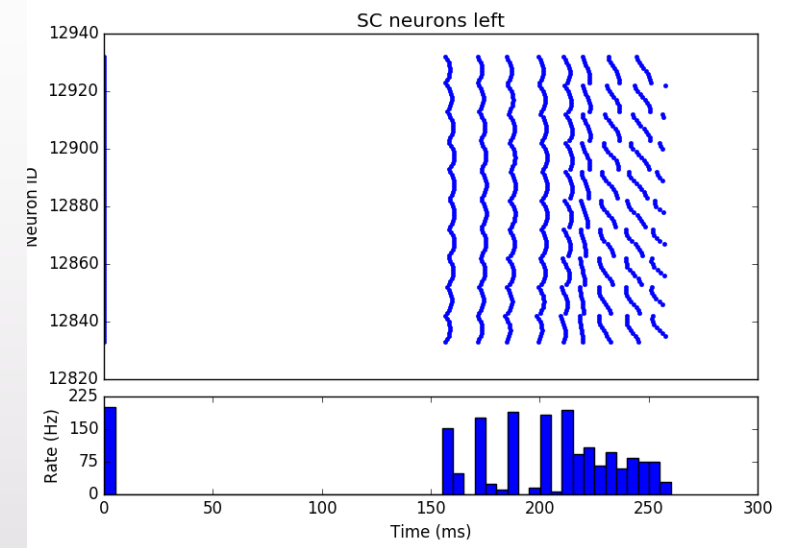




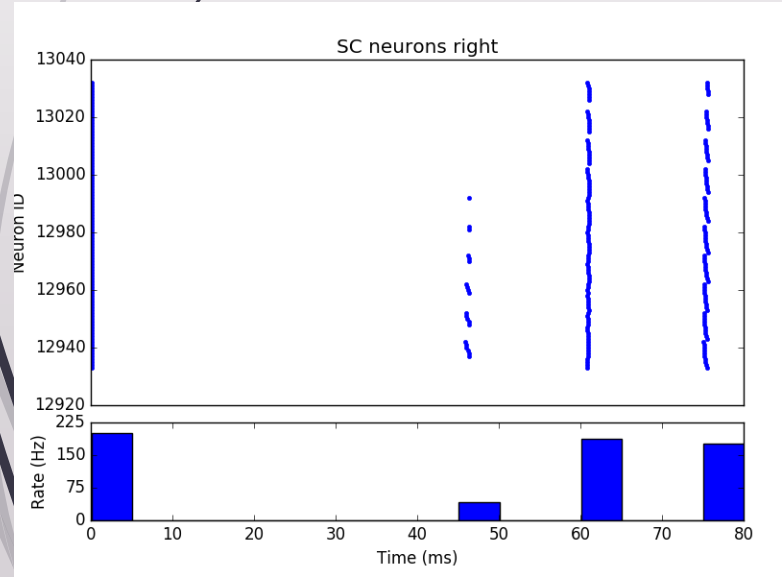
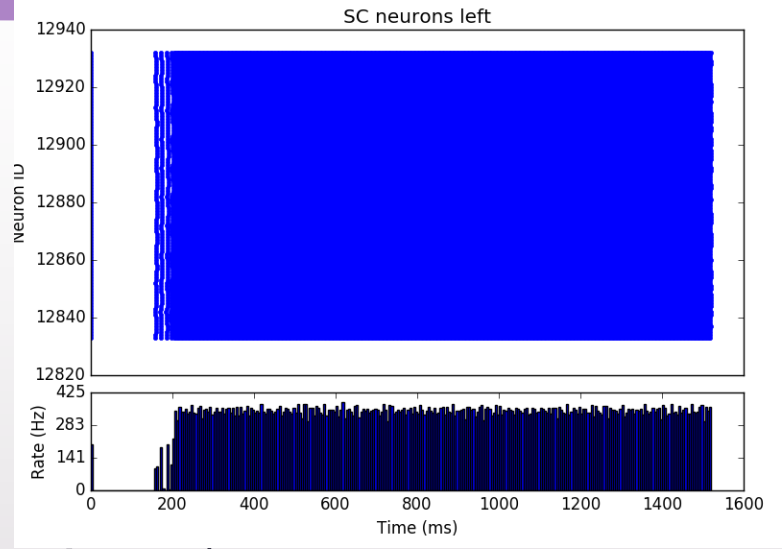
without lesion



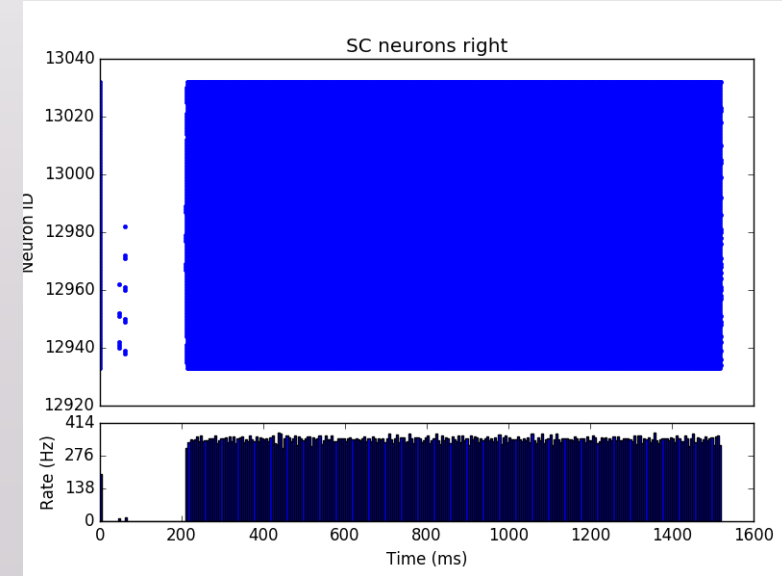
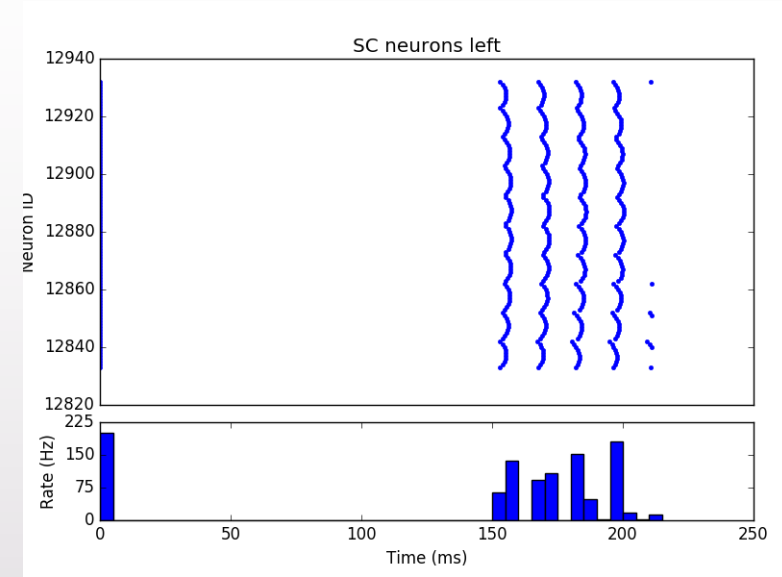
with lesion



without lesion

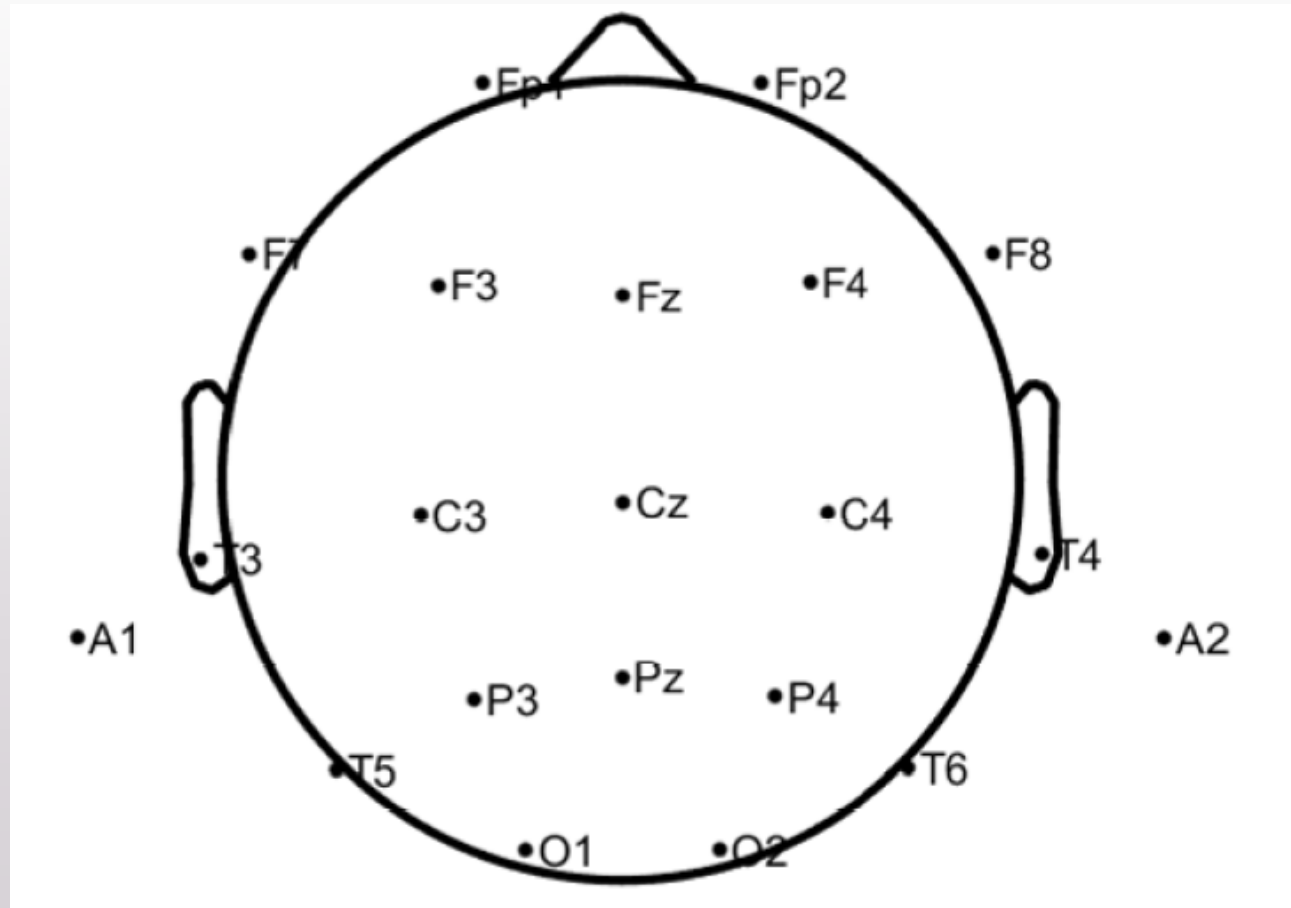


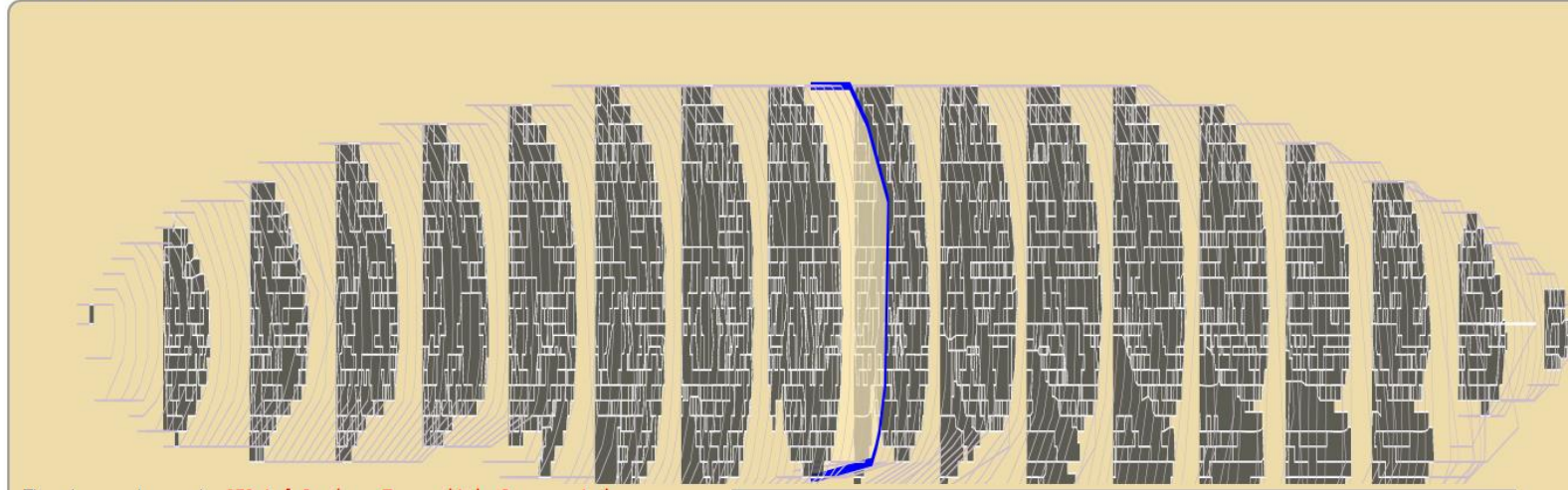
with lesion



nest ::

Използване на EEG измерванията на МОЗЪЧНАТА АКТИВНОСТ

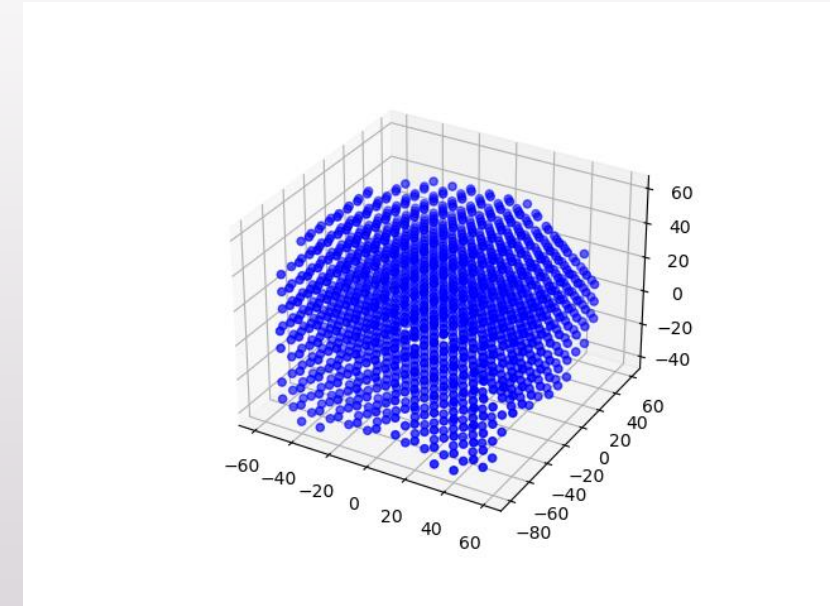


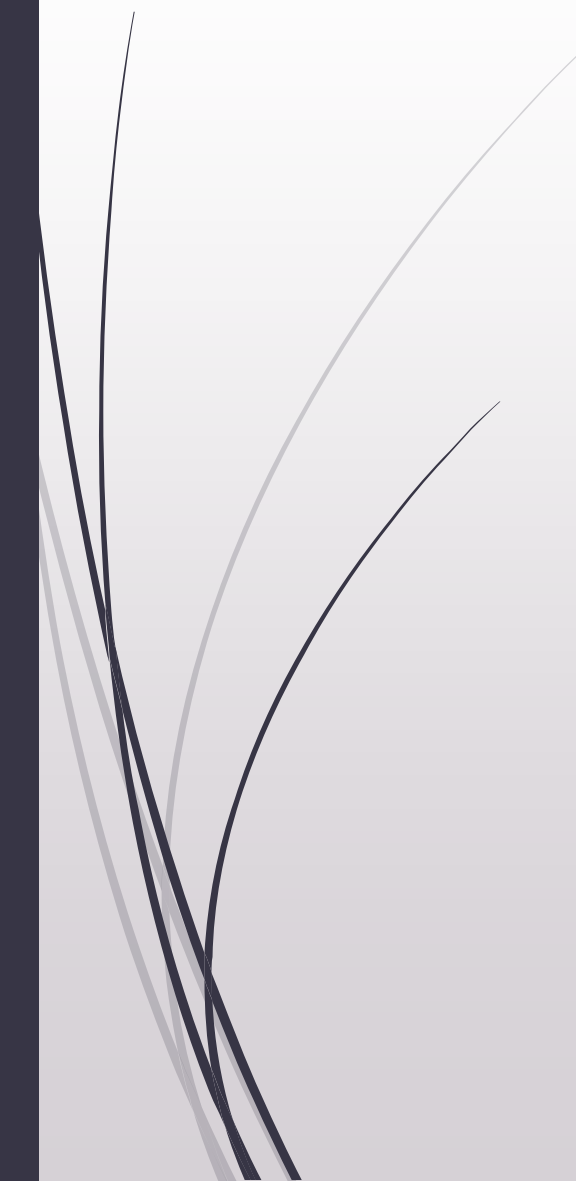


borders

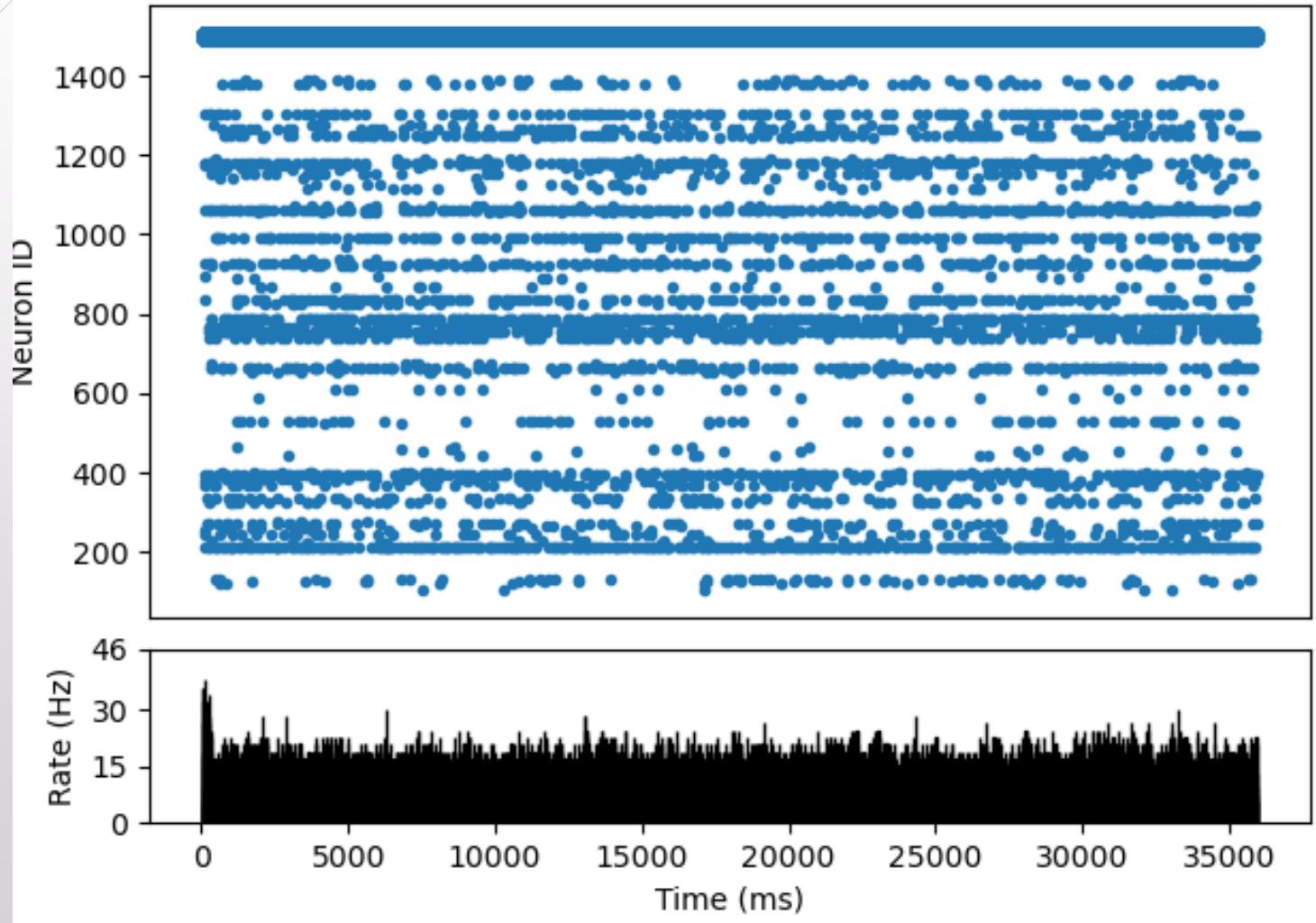
Regions in this slice (region hierarchy)

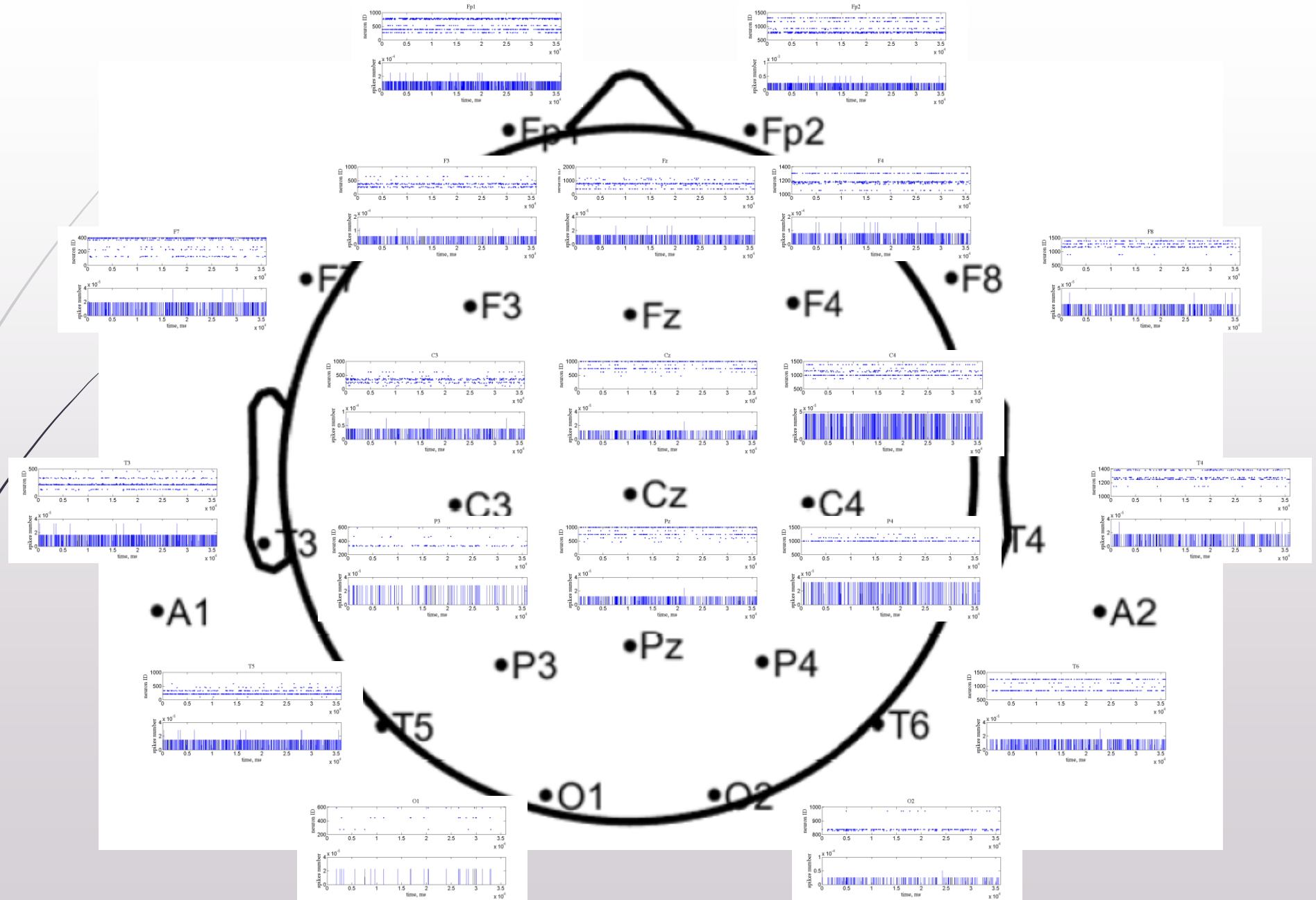
- 0 : *
- 10 : Left Cerebrum.Temporal Lobe
- 1009 : Left Cerebrum.Frontal Lobe.Medial Frontal Gyrus.Gray Matter.Brodmann area 6
- 1011 : Right Cerebrum.Frontal Lobe.Medial Frontal Gyrus.Gray Matter.Brodmann area 6
- 1045 : Left Cerebrum.Frontal Lobe.Paracentral Lobule.Gray Matter.Brodmann area 31
- 1046 : Left Cerebrum.Frontal Lobe.Paracentral Lobule
- 1047 : Inter-Hemispheric.,Paracentral Lobule
- 1049 : Right Cerebrum.Frontal Lobe.Paracentral Lobule.Gray Matter.Brodmann area 31
- 1051 : Left Cerebrum.Frontal Lobe.Paracentral Lobule.White Matter
- 1052 : Right Cerebrum.Frontal Lobe.Paracentral Lobule.White Matter
- 107 : Inter-Hemispheric
- 1077 : Left Cerebrum.Frontal Lobe.Superior Frontal Gyrus.Gray Matter.Brodmann area 6
- 1078 : Right Cerebrum.Frontal Lobe.Superior Frontal Gyrus.Gray Matter.Brodmann area 6
- 1094 : Right Cerebrum.Frontal Lobe.Sub-Gyral.Gray Matter.Brodmann area 6
- 12 : Right Cerebrum.Temporal Lobe.Inferior Temporal Gyrus
- 121 : Left Cerebrum.Temporal Lobe.Fusiform Gyrus
- 122 : Right Cerebrum.Temporal Lobe.Fusiform Gyrus
- 123 : Left Cerebrum.Temporal Lobe.Fusiform Gyrus.Gray Matter.Brodmann area 20
- 124 : Right Cerebrum.Temporal Lobe.Fusiform Gyrus.Gray Matter.Brodmann area 20
- 125 : Left Cerebrum.Limbic Lobe.Parahippocampal Gyrus
- 127 : Right Cerebrum.Limbic Lobe.Parahippocampal Gyrus
- 128 : Left Cerebrum.Temporal Lobe.Fusiform Gyrus.White Matter
- 129 : Left Cerebrum.Limbic Lobe.Parahippocampal Gyrus.Gray Matter.Brodmann area 36
- 13 : Right Cerebrum.Temporal Lobe.Inferior Temporal Gyrus.Gray Matter.Brodmann area 20
- 130 : Right Cerebrum.Limbic Lobe.Parahippocampal Gyrus.Gray Matter.Brodmann area 36
- 131 : Right Cerebrum.Temporal Lobe.Fusiform Gyrus.White Matter
- 133 : Left Cerebrum.Limbic Lobe.Parahippocampal Gyrus.White Matter





Raster plot from device '1510'







Благодаря за вниманието!