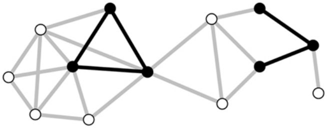
Modelling the nonrandom and dynamic structure of local cortical circuits

Felix Z. Hoffmann

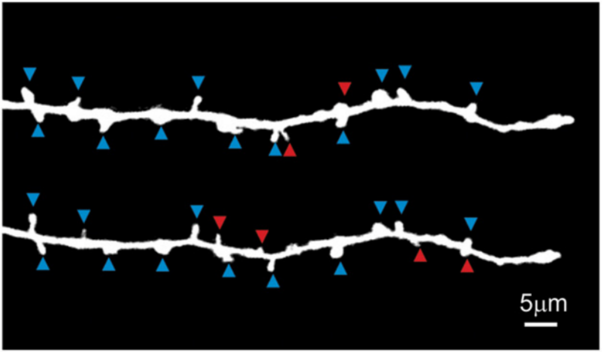
Slides: bit.ly/bx18s



Bernstein Conference 2018 Satellite Workshop:
Adaptivity and Inhomogeneity in Neuronal Networks

The dynamic connectome

At the synapse level, brain circuitry is constantly making new connections and abolishing old ones



Loewenstein et al. 2015

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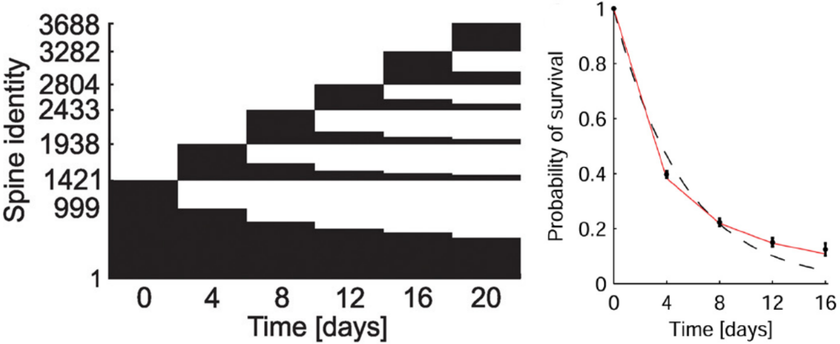
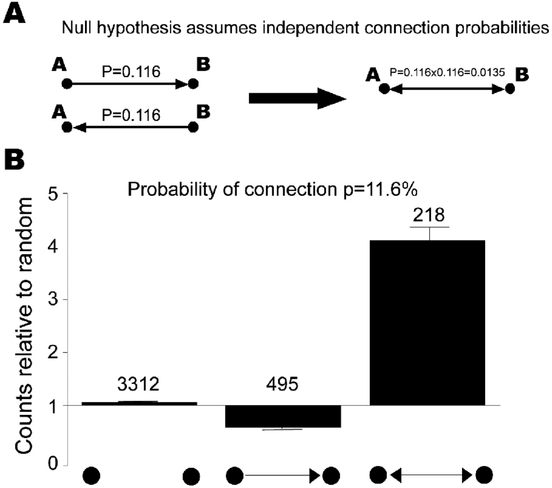


Loewenstein et al. 2015

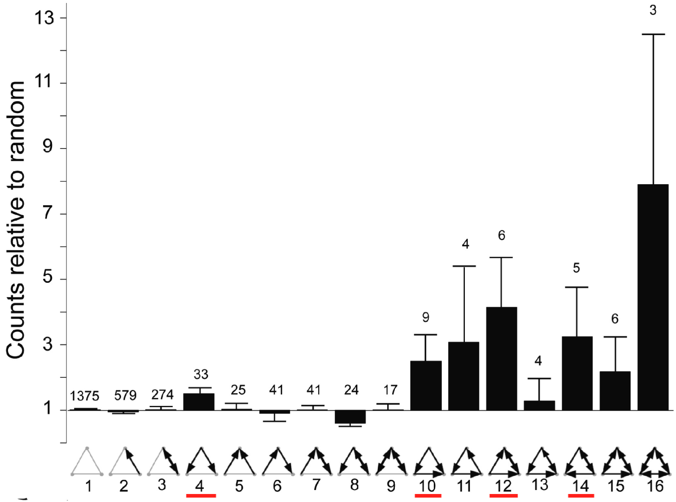
Robust nonrandom connectivity patterns



1. Overrepresentation of reciprocal connections

Song et al. 2005

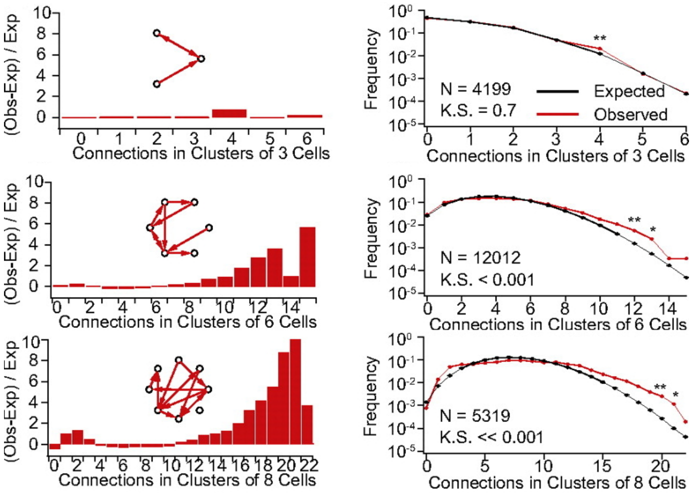
Robust nonrandom connectivity patterns



2. Characteristic occurrence of triplet motifs

Song et al. 2005; Perin et al. 2011

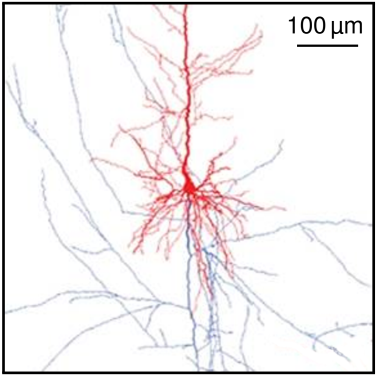
Robust nonrandom connectivity patterns



3. High degree of connectivity in clusters occurs frequently

Perin et al. 2011

Morphological anisotropy in spatial connectivity



axon

morph. data from Romand et al. 2011

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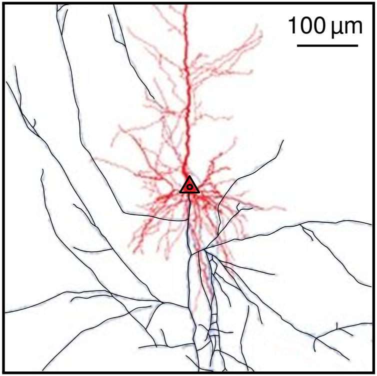

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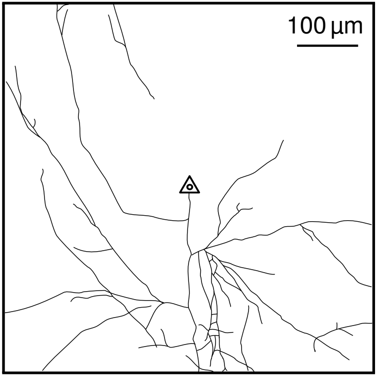

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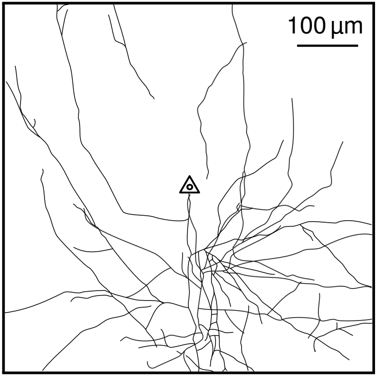

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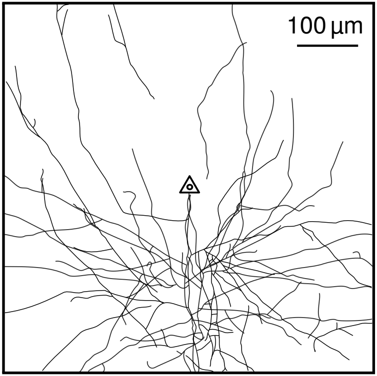

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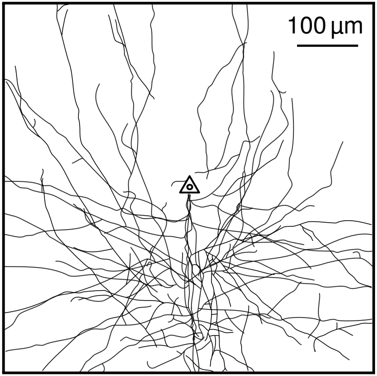

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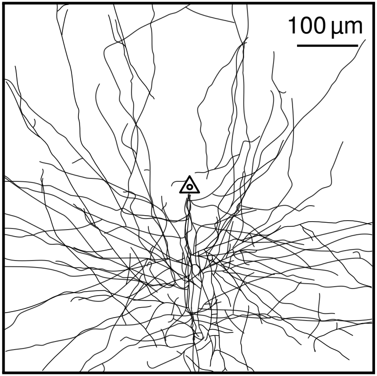

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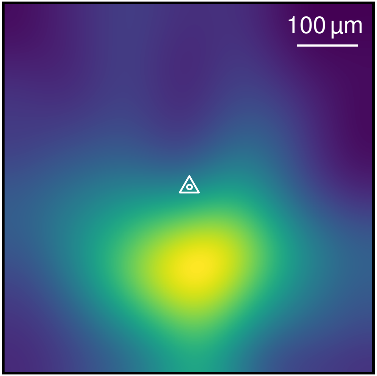

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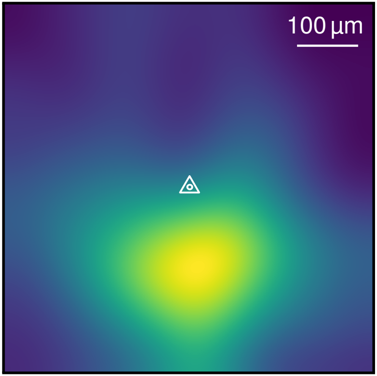

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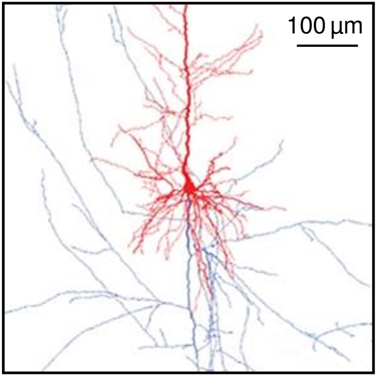
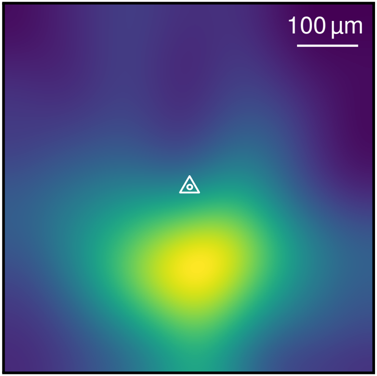


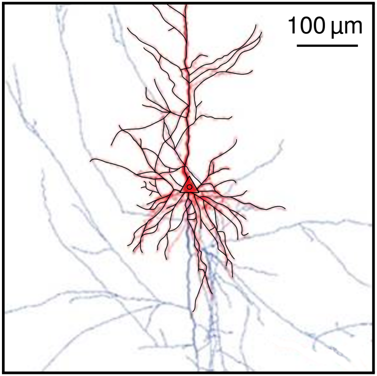
dendrite

morph. data from Romand et al. 2011

Morphological anisotropy in spatial connectivity



axon



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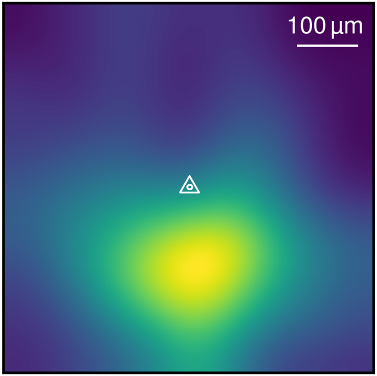
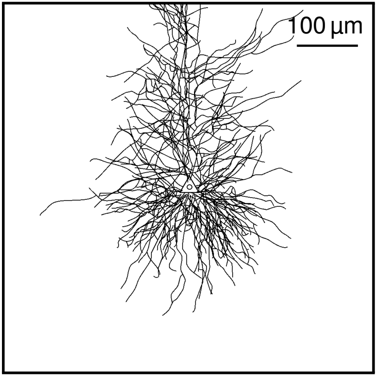


axon



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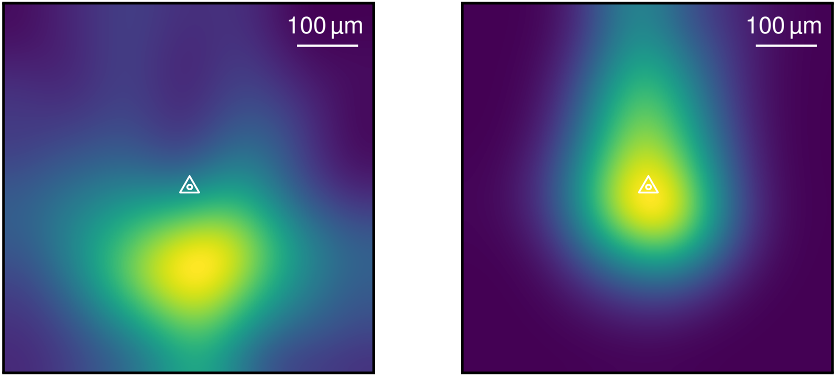

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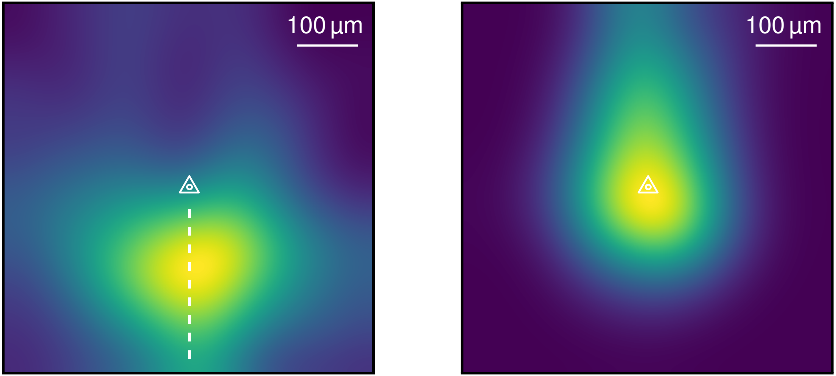

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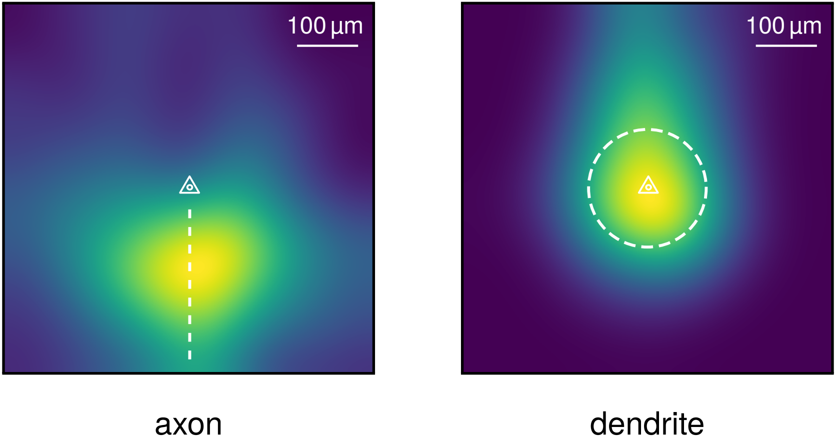
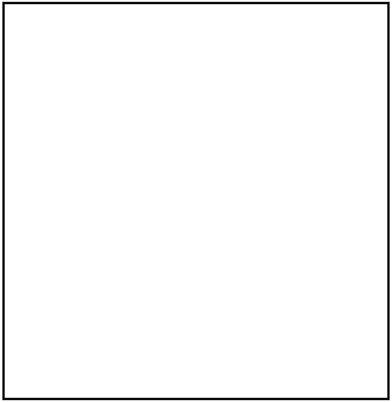


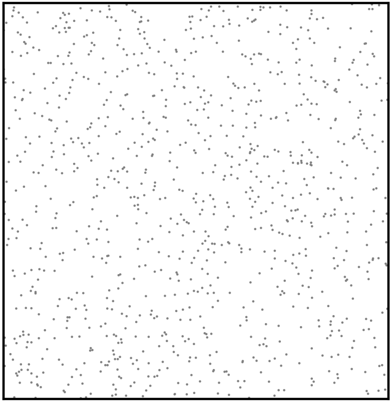
morph. data from Romand et al. 2011

Anisotropic network model



Distribute N = *1000* neurons randomly on a square surface

Anisotropic network model



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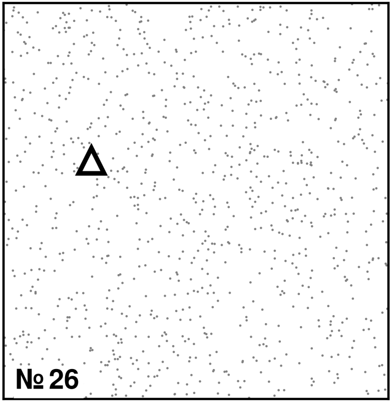
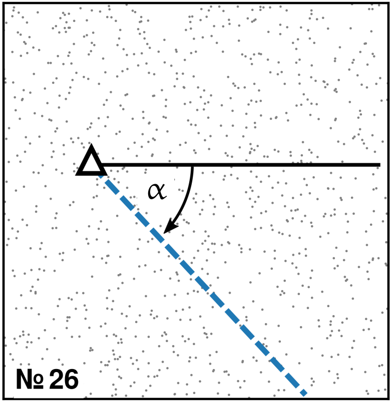


Distribute $N = 1000$ neurons randomly on a square surface

For each neuron

Anisotropic network model

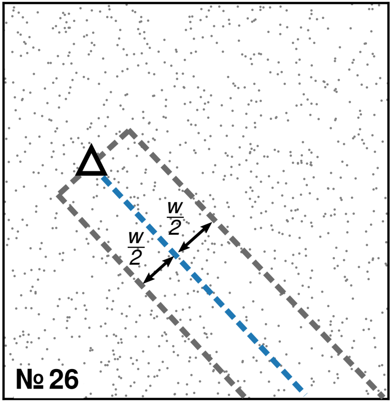


Distribute $N = 1000$ neurons randomly on a square surface

For each neuron

- assign a random angle α

Anisotropic network model

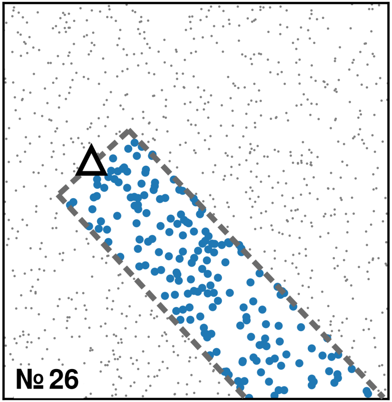


Distribute $N = 1000$ neurons randomly on a square surface

For each neuron

- assign a random angle α
- find targets within distance $w/2$ of α-projection

Anisotropic network model



Distribute $N = 1000$ neurons randomly on a square surface

For each neuron

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- find targets within distance $w/2$ of α-projection
- connect to targets

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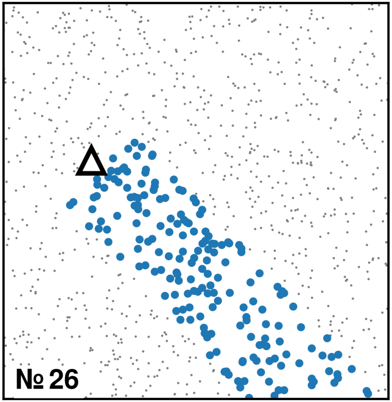

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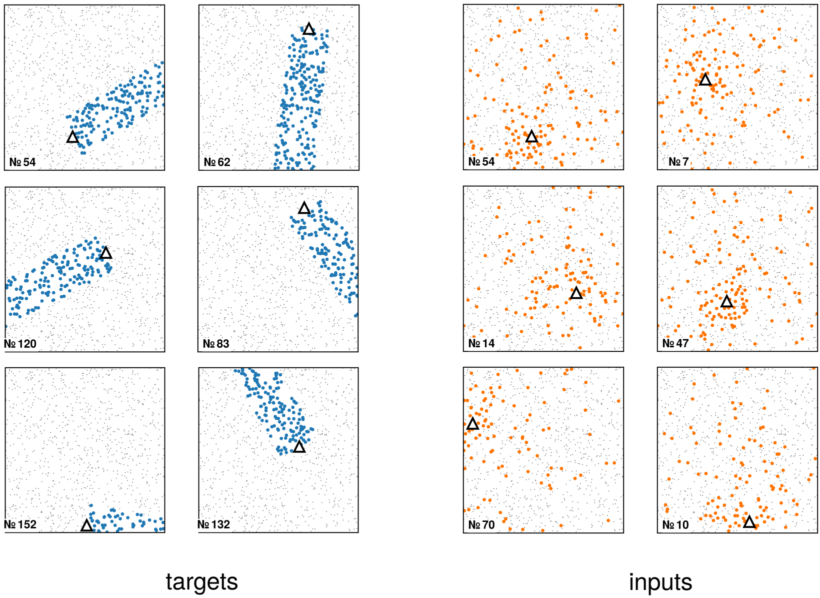

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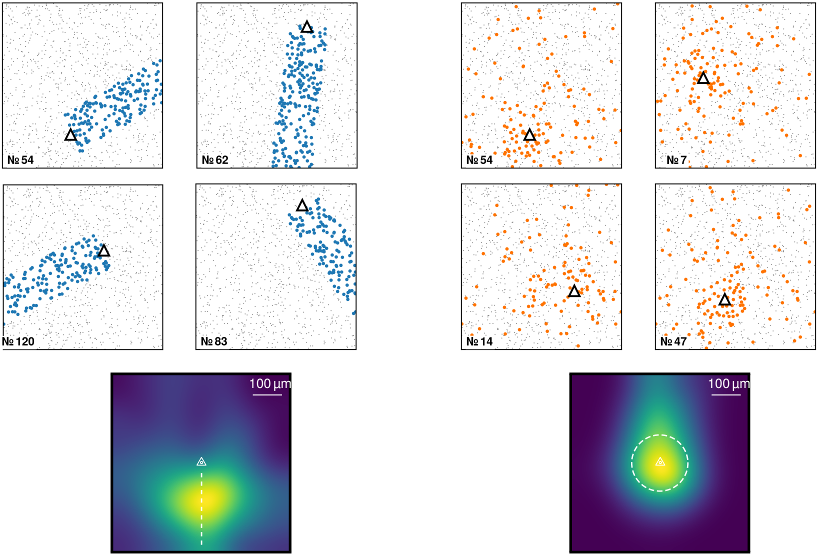

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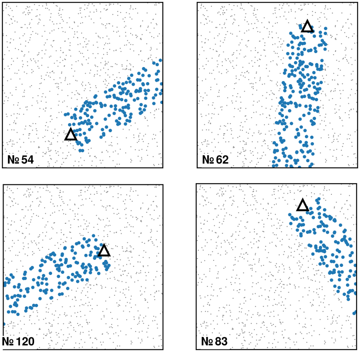
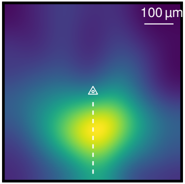




Model parameters

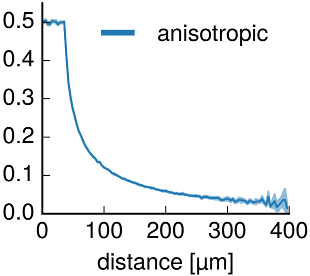
Number of nodes N = *1000*

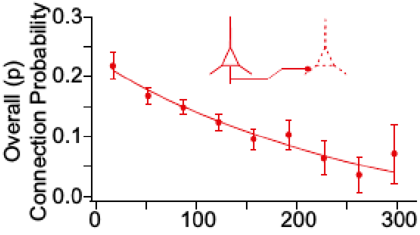
edge length of surface l = 296 µm

width w = 74.6 µm

> l and w tuned to give connection density of p = *0.116*

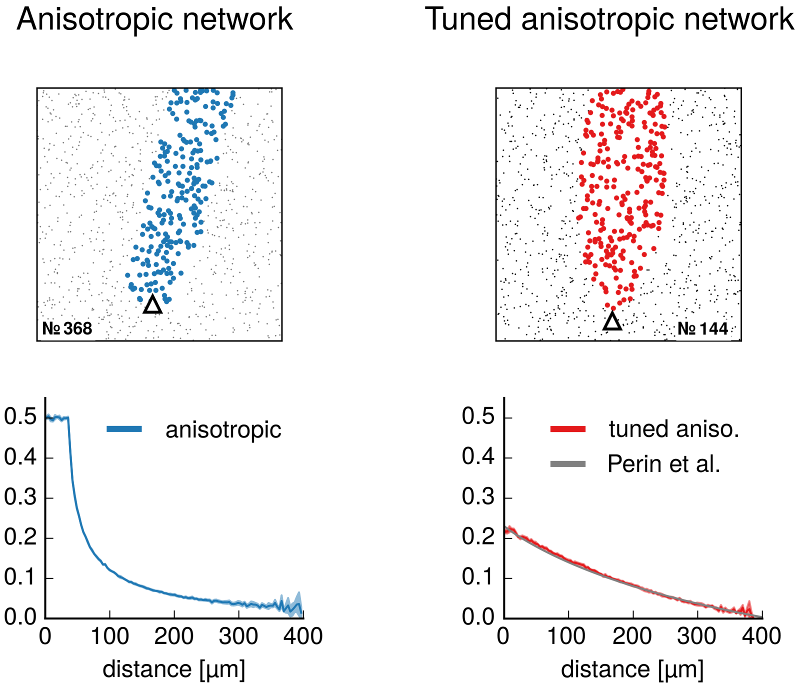
Distance-dependent connectivity in anisotropic networks



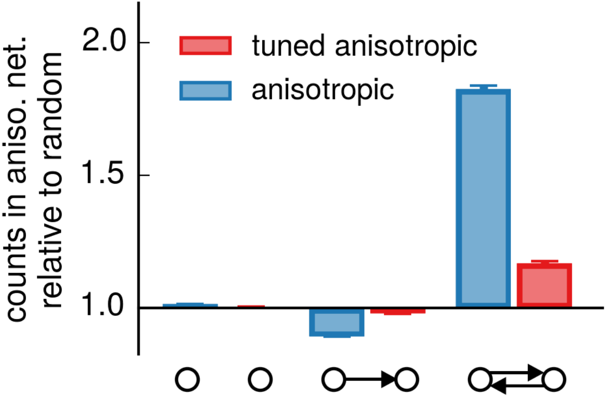


anisotropic network

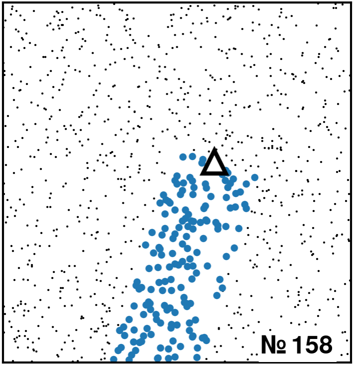
somatosensory cortex
Perin et al. (2011)


Anisotropic network
Tuned anisotropic network
№ 368
№ 144
anisotropic
tuned aniso.
Perin et al.
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
distance [μm]

Results – Overrepresentation of reciprocal connections



Rewiring anisotropic networks



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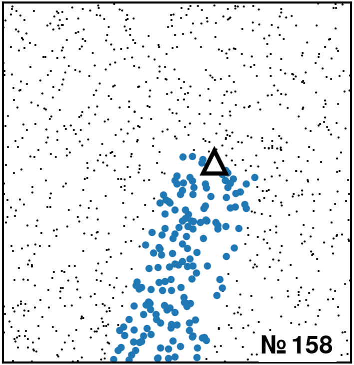

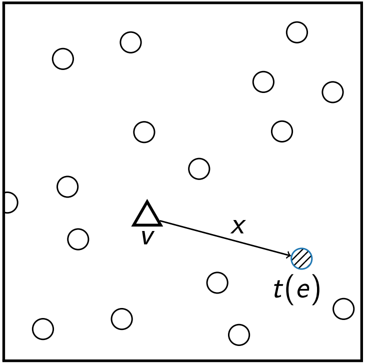

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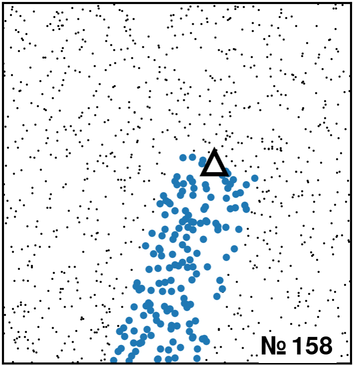

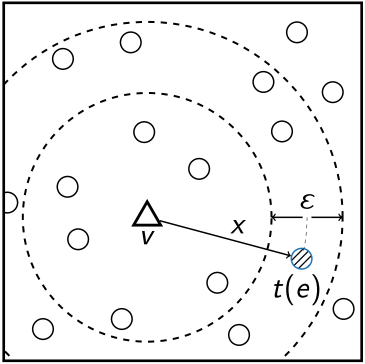

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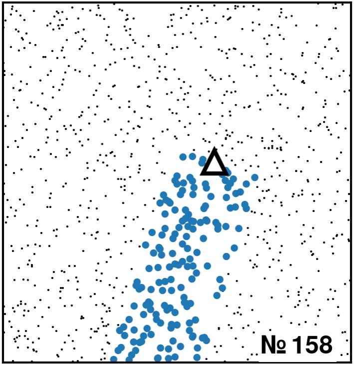

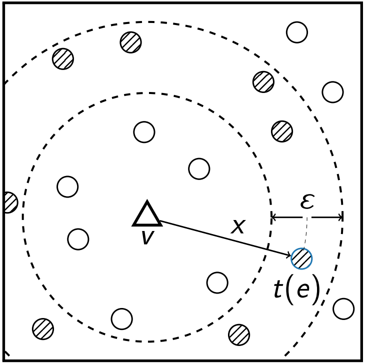

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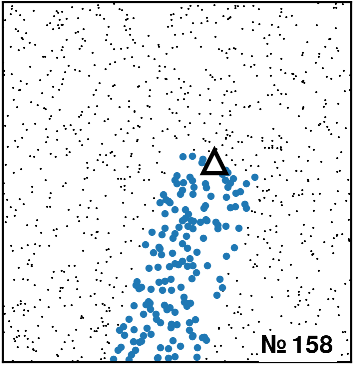

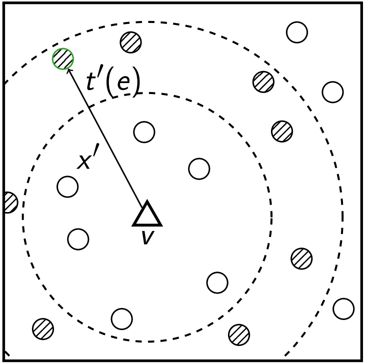

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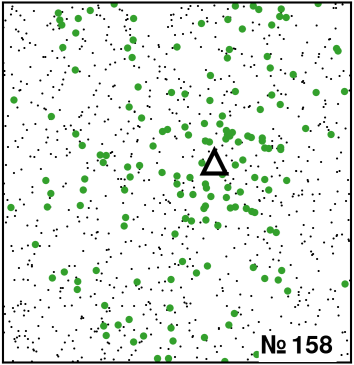

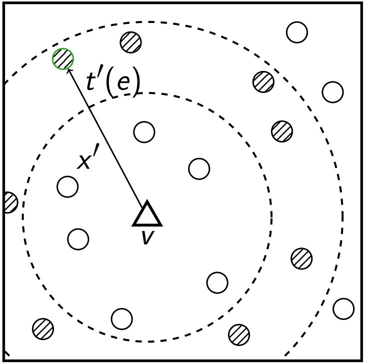

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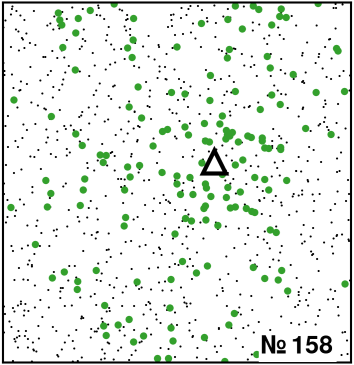

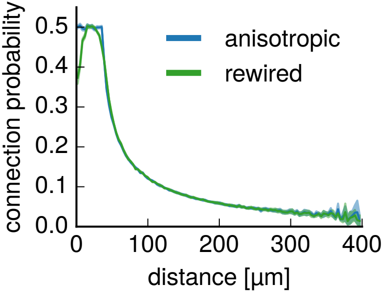

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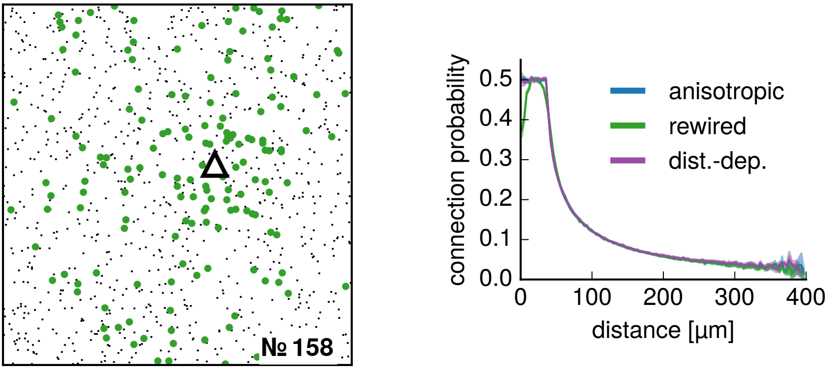
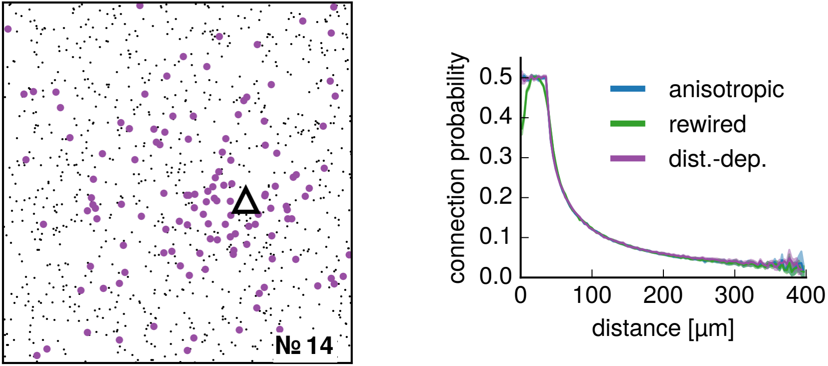
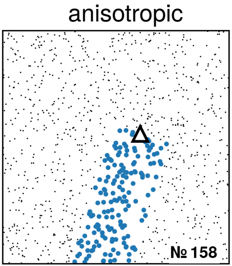


Distance-dependent network



Network model overview



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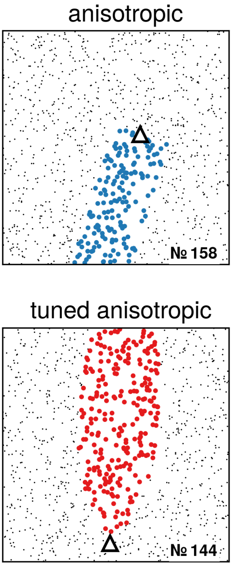

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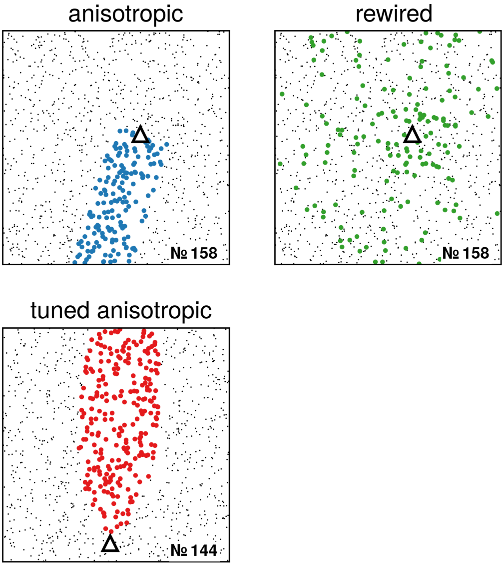

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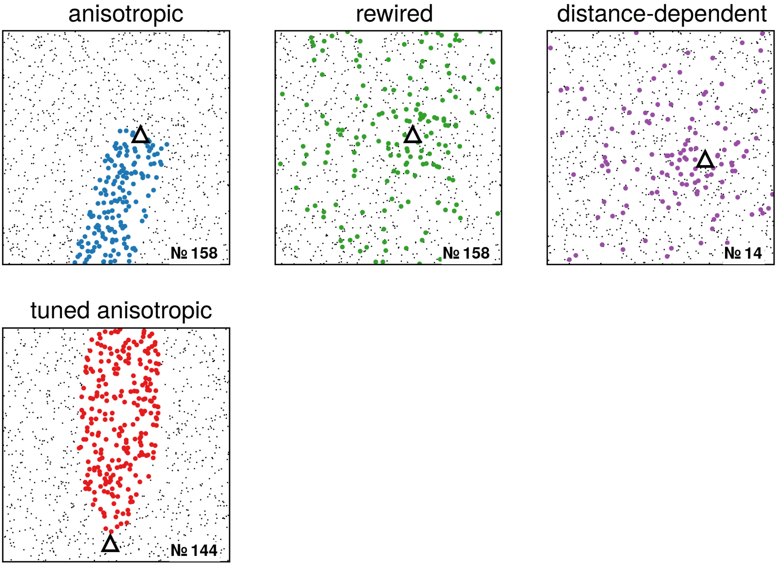

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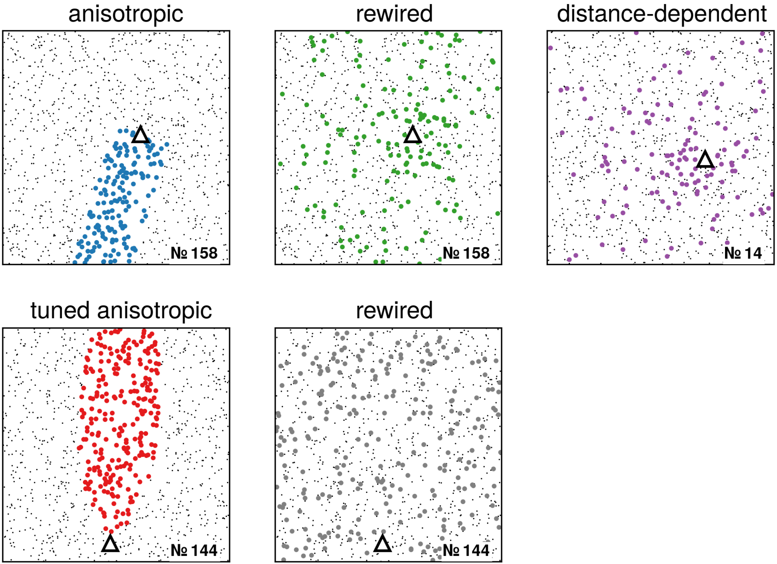

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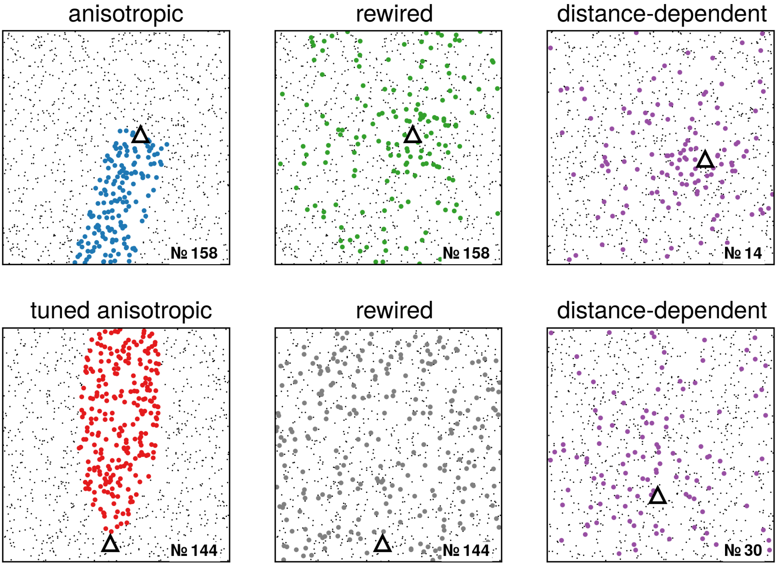
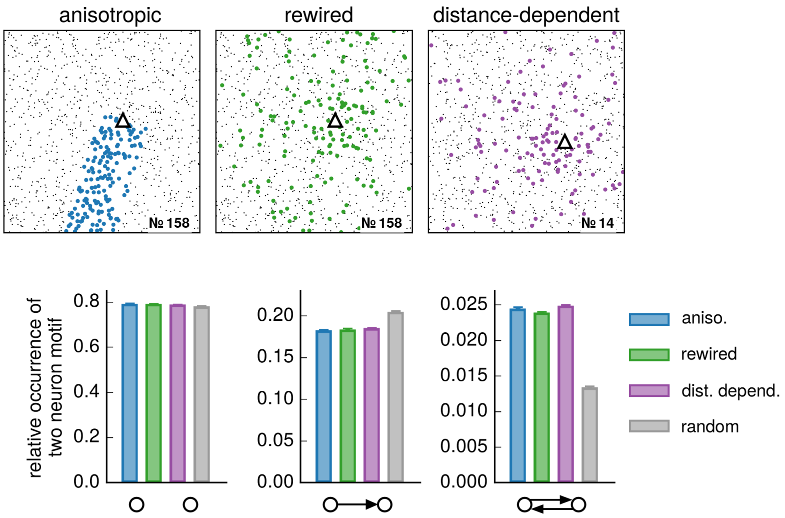


Results – Overrepresentation of reciprocal connections



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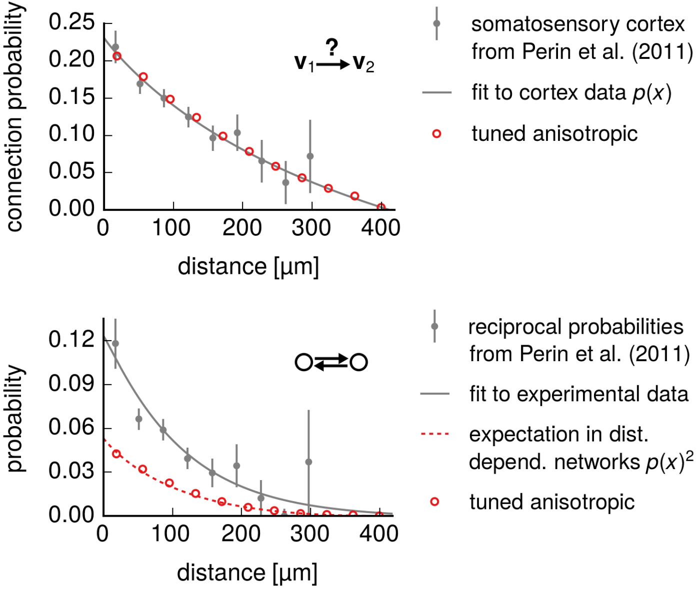

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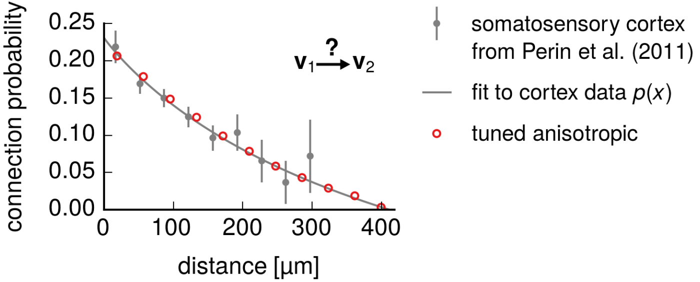
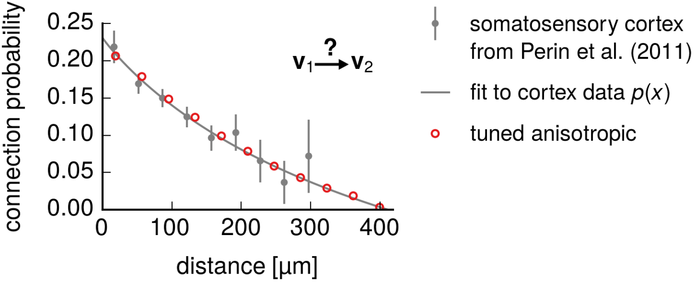


Other sources for the overrepresentation of bidirectional connections?

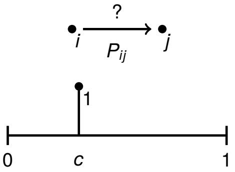
Results – Overrepresentation of reciprocal connections



Other sources for the overrepresentation of bidirectional connections?

⇒ Hoffmann, FZ and Triesch, J (2017). Nonrandom Network Connectivity Comes in Pairs. *Network Neuroscience*

Standard random network model



Probability of connection a <u>constant</u> P_{ij},

$$P_{ij} = c$$

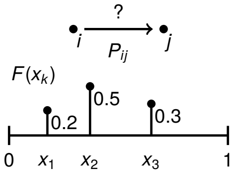
Overall connection probability

$$\mu = P_{ij} = c$$

Bidirectional connection

$$P_{\text{bidir}} = P_{ij} P_{ji} = c^2$$

Varying connection probabilities



Probability of connection a <u>random variable</u> P_{ij},

$$\textbf{Prob}(P_{ij} = x_k) = F(x_k)$$

Overall connection probability

$$\mu = \sum_{k=1}^{m} F(x_k) x_k$$

Bidirectional connection

$$P_{\text{bidir}} = \sum_{k=1}^{m} \sum_{l=1}^{m} F(x_k) x_k F(x_l | x_k) x_l$$

Assume that connection probabilities within pairs are identical,

$$F(x_l|x_k) = \begin{cases} 1 & \text{if } l = k \\ 0 & \text{otherwise.} \end{cases}$$

Then

$$P_{\text{bidir}} = \sum_{k=1}^{m} \sum_{l=1}^{m} F(x_k) x_k F(x_l|x_k) x_l = \sum_{k=1}^{m} F(x_k) x_k^2.$$

Relative overrepresentation ρ is the fraction

$$\rho = \frac{P_{\text{bidir}}}{\mu^2} = \frac{\sum_{k=1}^{m} F(x_k) x_k^2}{\left(\sum_{k=1}^{m} F(x_k) x_k\right)^2}.$$

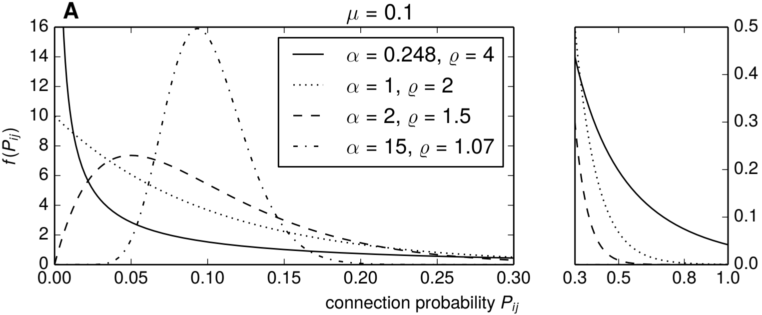
By Jensen's inequality,

$$\left(\sum_{k=1}^{m} F(x_k) x_k\right)^2 \leq \sum_{k=1}^{m} F(x_k) x_k^2 \quad \text{and thus} \quad \rho \geq 1.$$

Hoffmann and Triesch 2017

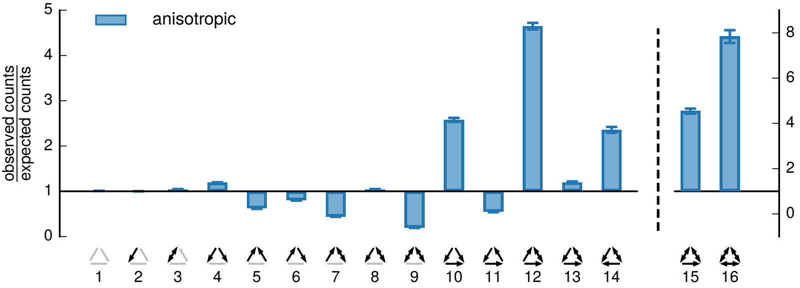
- multiple neuron properties may compound to give rise to broad connection probability distribution

- for example, higher connection probability in functionally related cells (Lee et al. 2016)

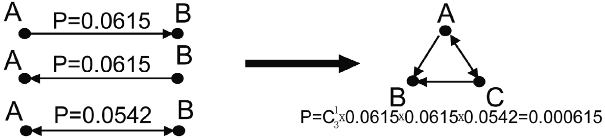


Hoffmann and Triesch 2017

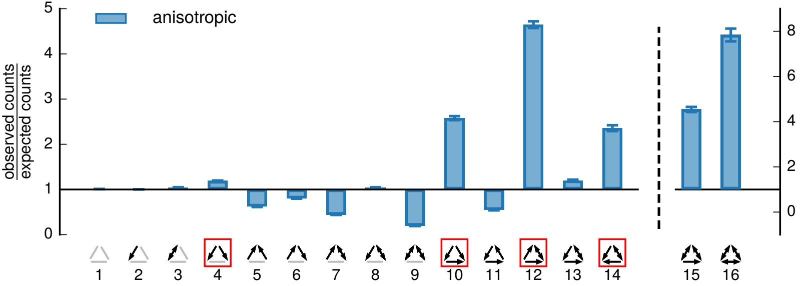
Three neuron motifs



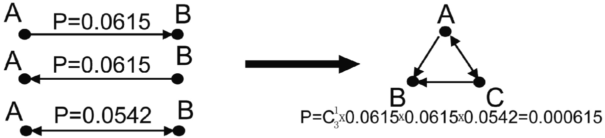
Null hypothesis assumes independent combination of pair connection probabilities



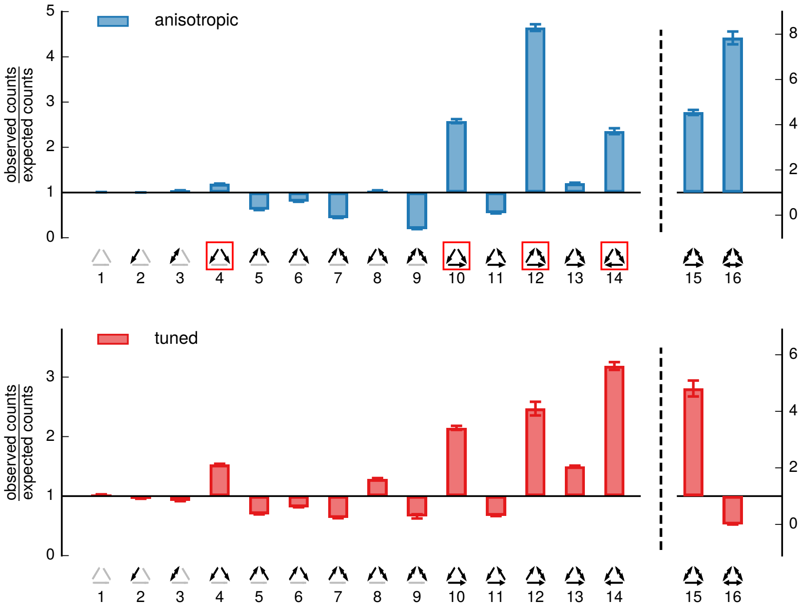
Three neuron motifs



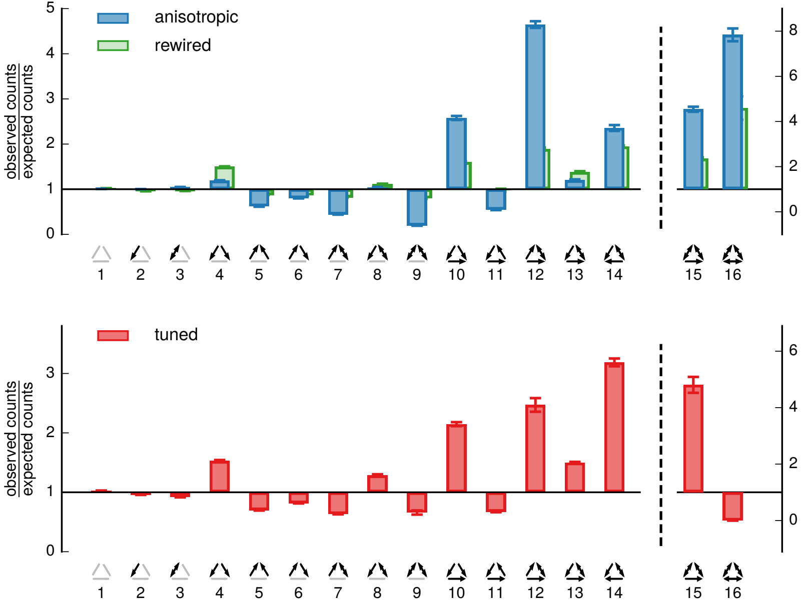
Null hypothesis assumes independent combination of pair connection probabilities



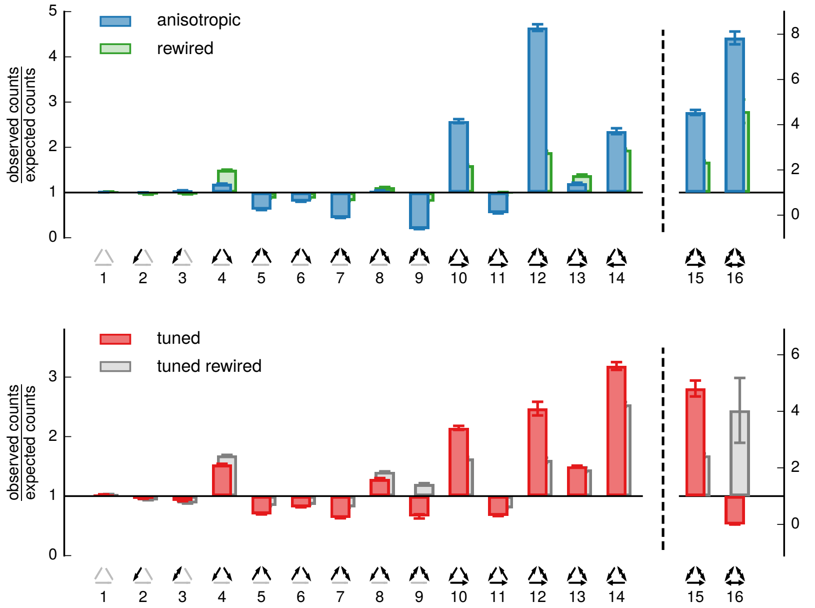
Three neuron motifs



Three neuron motifs



Three neuron motifs



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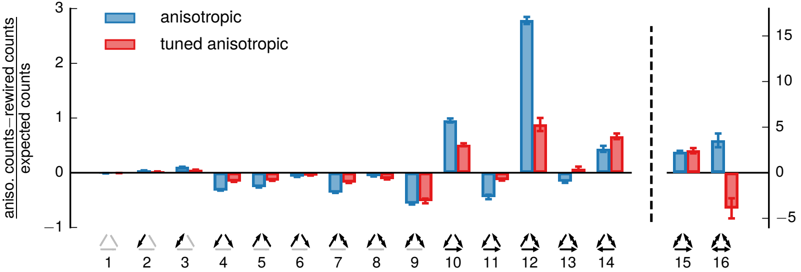

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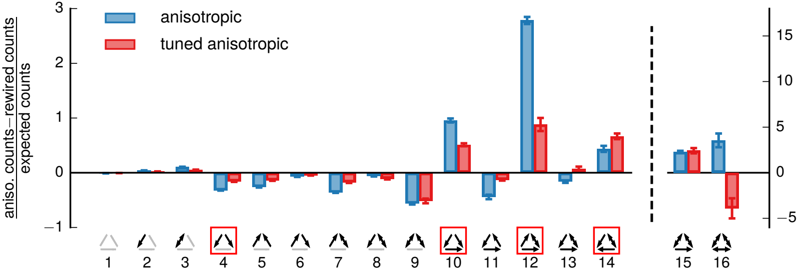

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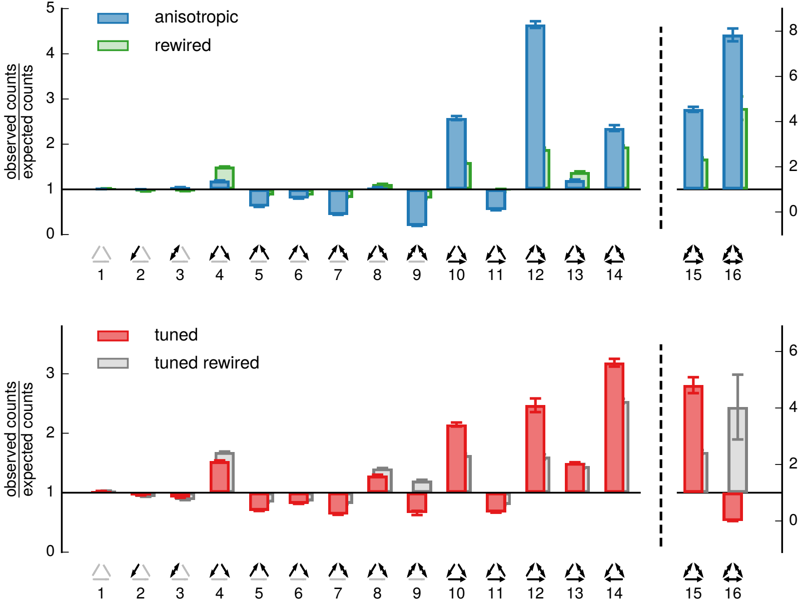

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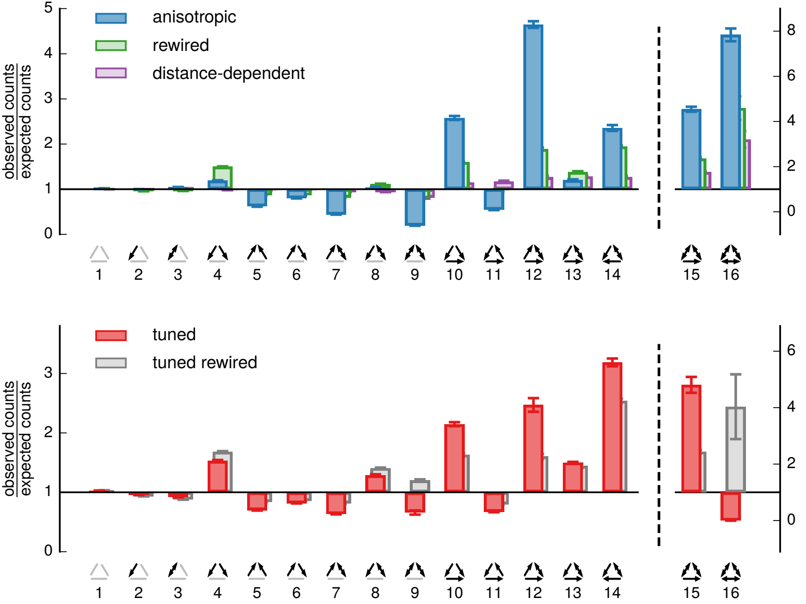

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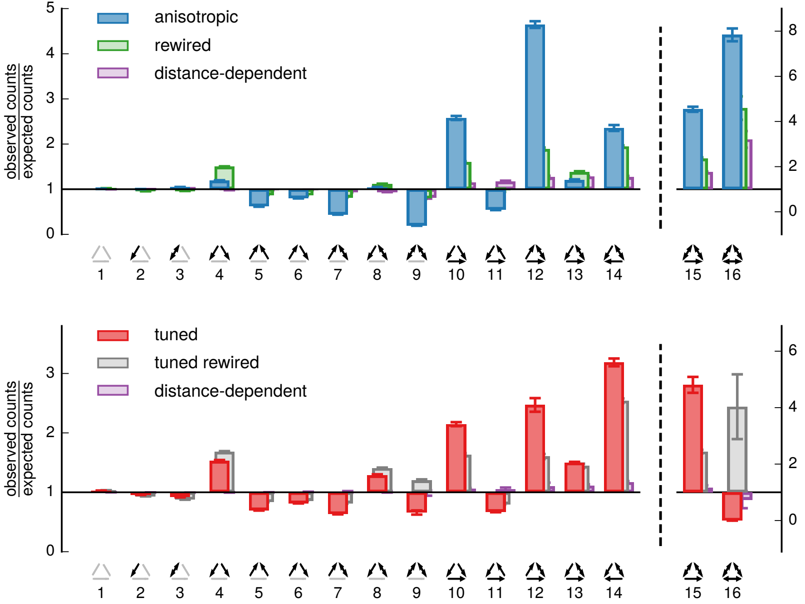

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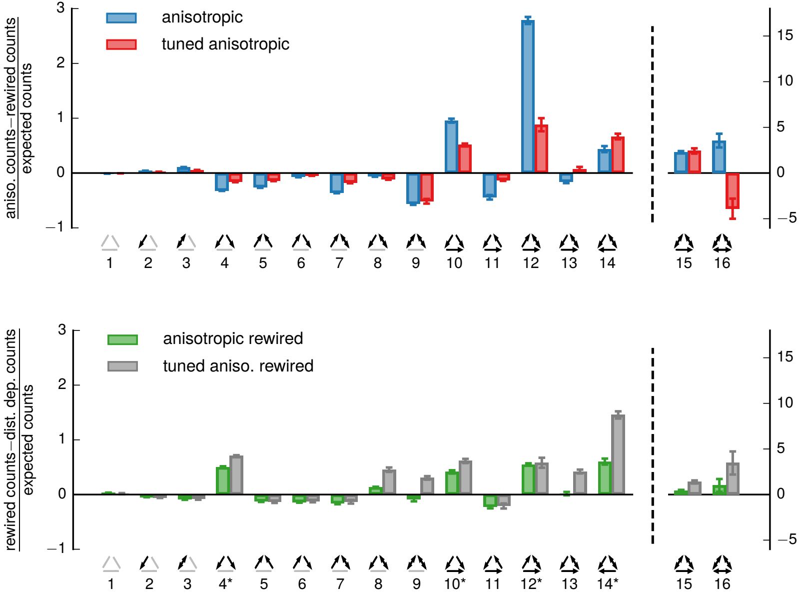

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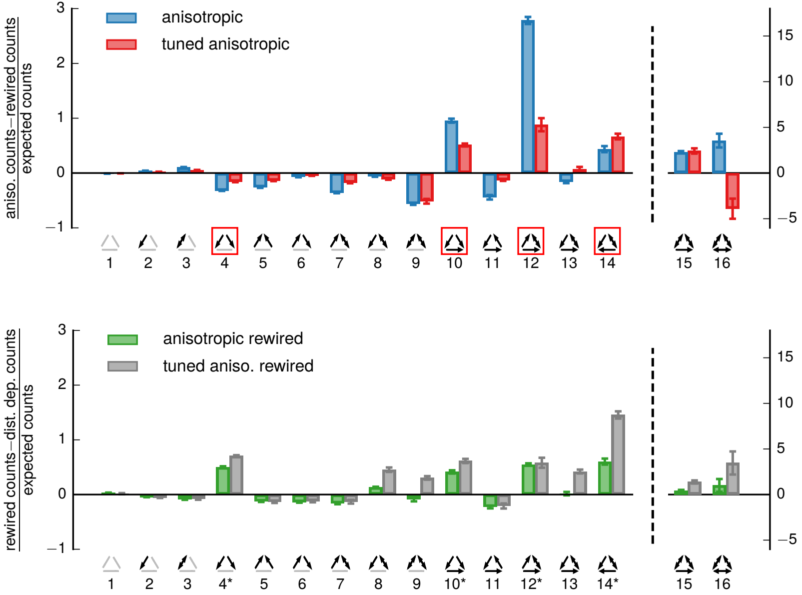
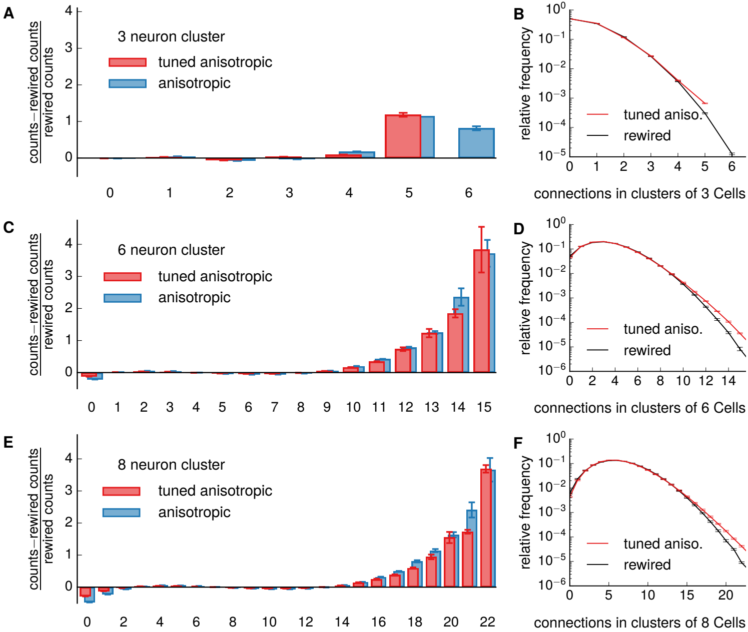
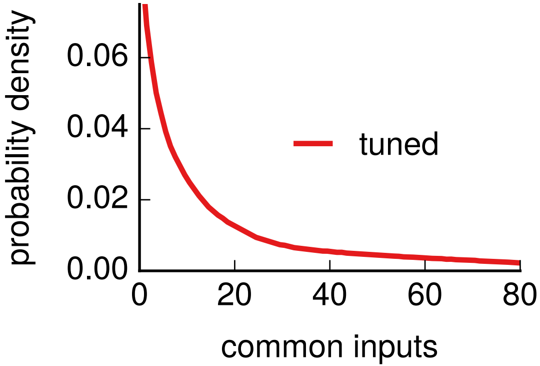


Connection density in clusters



Common inputs statistics



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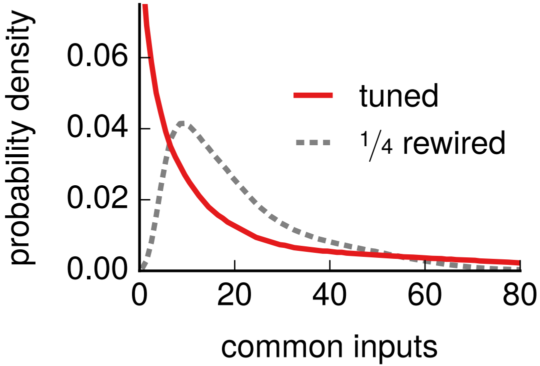

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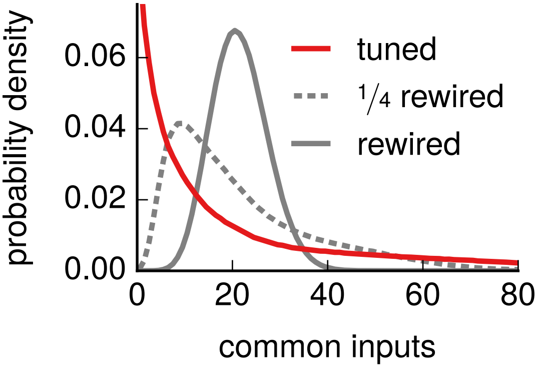

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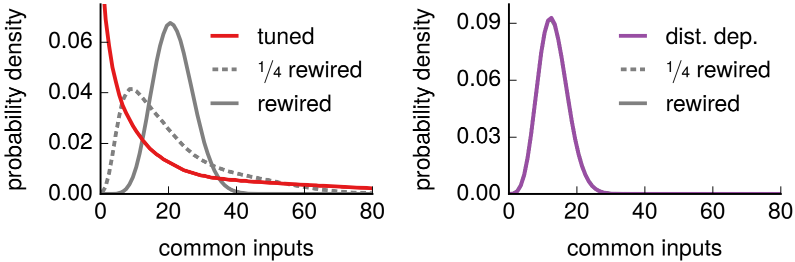

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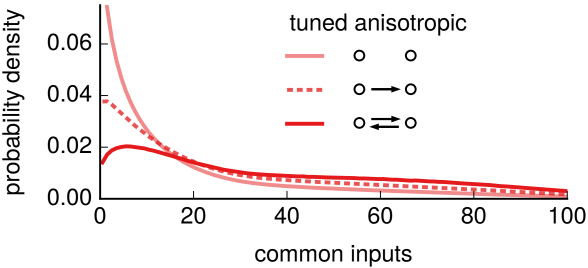

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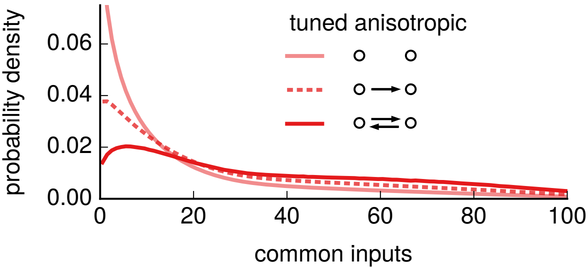
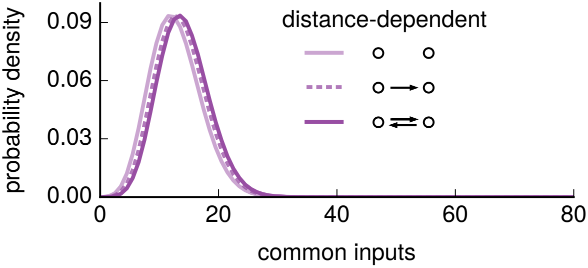




Summary 1-1

Model

- anisotropy in spatial connectivity as a result of stereotypical axon and dendrite morphology
- anisotropic network as a simple model to test how anisotropy in spatial connectivity impacts network connectivity

Results

- reciprocal connections are overrepresented but only due induced distance-dependency
- various neuron properties (such as functional similarity) may compound with distance-dependency to induce observed reciprocity in cortical circuits

Summary 1-2

Results

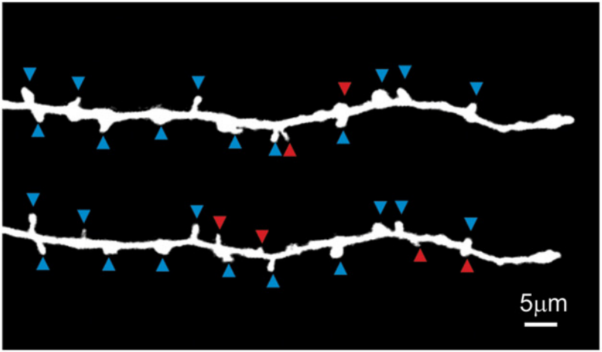
- specific three neuron motifs occur over- and underrepresented due to anisotropy matching data from cortical circuits
- observed frequent occurrence of high connection counts in neuron groups as a direct result of anisotropy in spatial connectivity

Predictions

- anisotropic network model predicts broad distributions of common inputs for neuron pairs
- anisotropic network model predicts stronger sensitivity to connection type for common input distributions

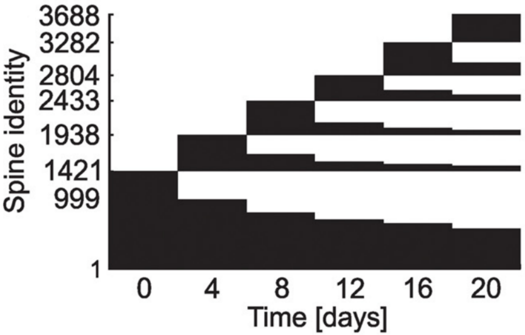
The dynamic connectome

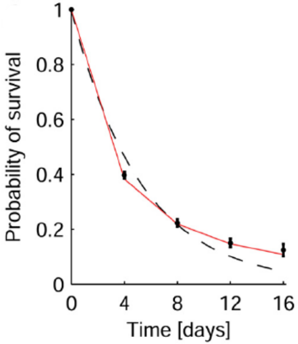
At the synapse level, brain circuitry is constantly making new connections and abolishing old ones



Loewenstein et al. 2015

The dynamic connectome





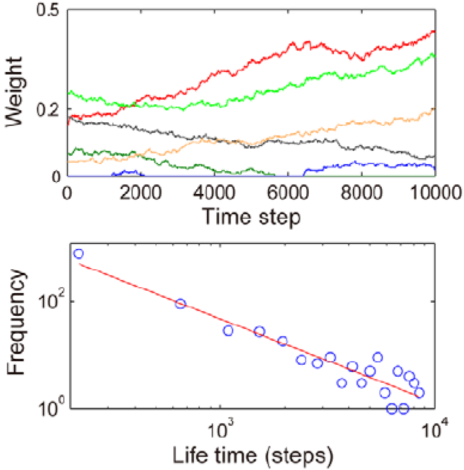
Survival probability of $\rho(t) = (t + 1)^{-\gamma}$ with $\gamma \approx 1.4$,

equivalently lifetime distribution of $f(t) = \gamma(t + 1)^{-(\gamma+1)}$

Loewenstein et al. 2015

Synapse dynamics in self-organizing recurrent networks

Power law synaptic lifetime distribution – Zheng et al. 2013



Zheng et al. 2013

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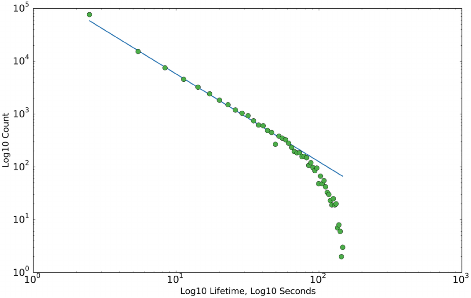
Extension to leaky integrate-and-fire neuron – Miner and Triesch 2016



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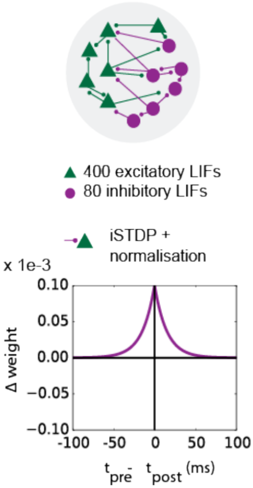
Synapse dynamics under inclusion of iSTDP – Kleberg and Triesch 2018



Kleberg and Triesch 2018

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Triesch lab

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