Synaptic efficacy tunes speed of activity propagation through chains of bistable neural assemblies

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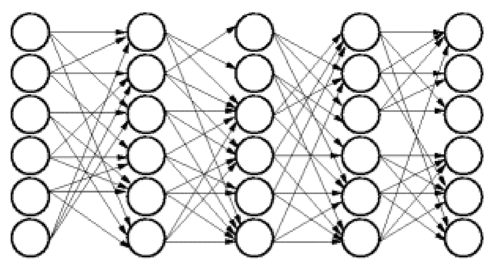
An alternative model of stable activity propagation in cortical networks

Popular models of activity propagation (synfire chain [1] and propagation of firing rates [2]) suffer from problems:

- Feed-forward structures (unidirectional fashion): have not been found experimentally so far.
- High propagation speed of the activity: unable to model slow behavioral functions like the control of arm movements.



We propose a bidirectional chain of bistable neuronal assemblies:

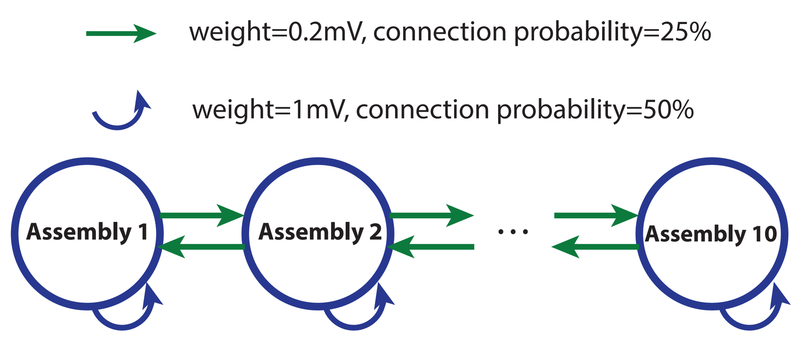
- No need for feed-forward structure
- Propagates activity forwards, backwards, or in both directions
- Regulation of propagation speed through synaptic weights

Bidirectional chain of bistable assemblies

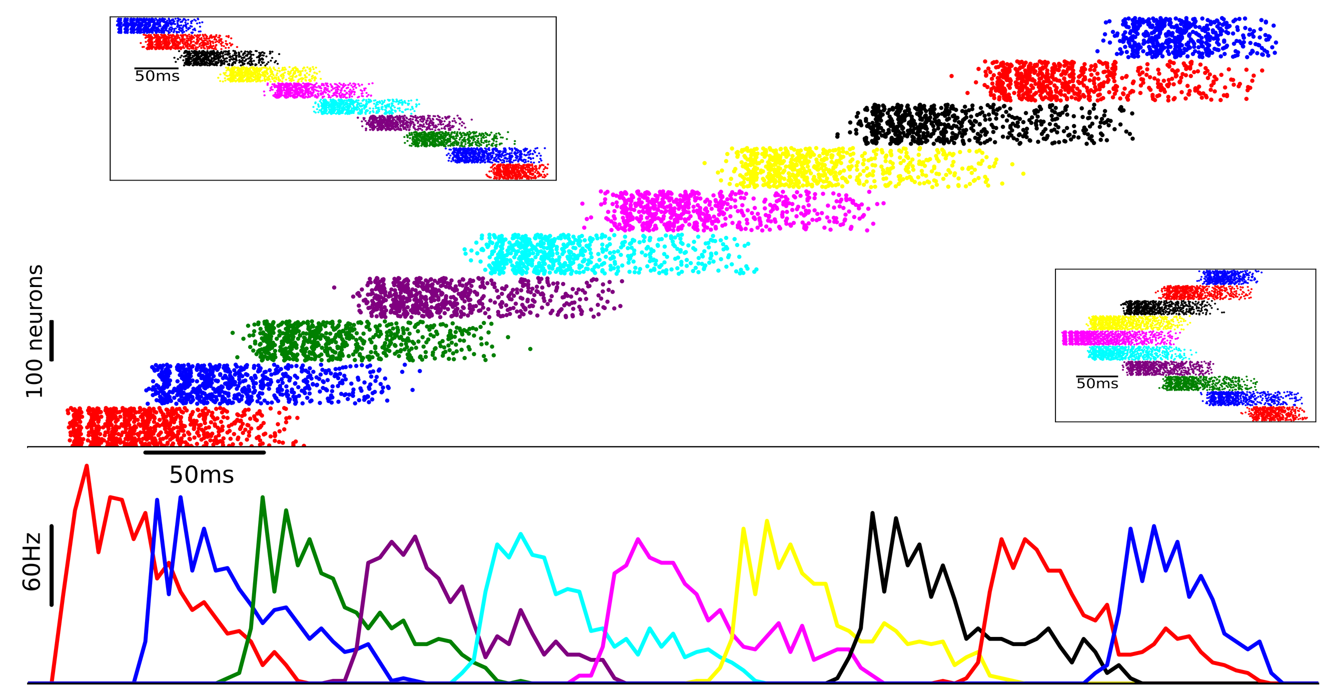
Inside assembly: 100 excitatory neurons, dense connectivity, strong synapses, short-term depression [3]

Between assemblies: sparse connectivity, weak synapses

Clustered connectivity is supported by experimental data observed in the cortex [4].



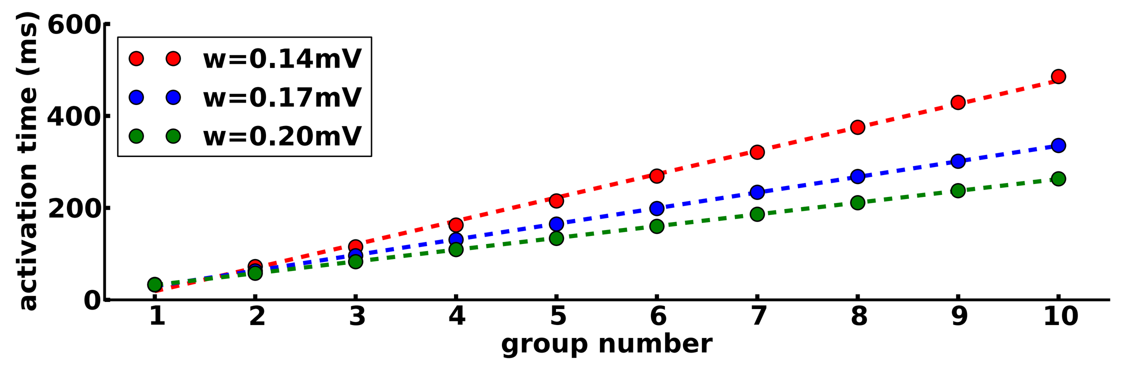
Based on the place of initial stimulation (transient external Poisson noise), the chain propagates the activity forwards, backwards, or in both directions simultaneously.



Inter-assembly synaptic weights control the propagation speed

Activation time of assembly: minimum time after which all neurons have fired at least once.

Weakening inter-assembly synapses ➔ reduction of speed



Analysis of bistable assembly dynamics

A common mean-field method is used for analyzing the dynamics.

Two relations between firing rate and synaptic current form an iterative map:

1. Noisy gain function [5]:

$$r = g(\langle I_{\mathrm{syn}}\rangle, \sigma) = \left(\tau_{\mathrm{ref}} + \tau_{\mathrm{m}}\sqrt{\pi}\int_{y_{\mathrm{r}}}^{y_{\mathrm{th}}} e^{x^2}(1+\mathrm{erf}(x))dx\right)^{-1}$$

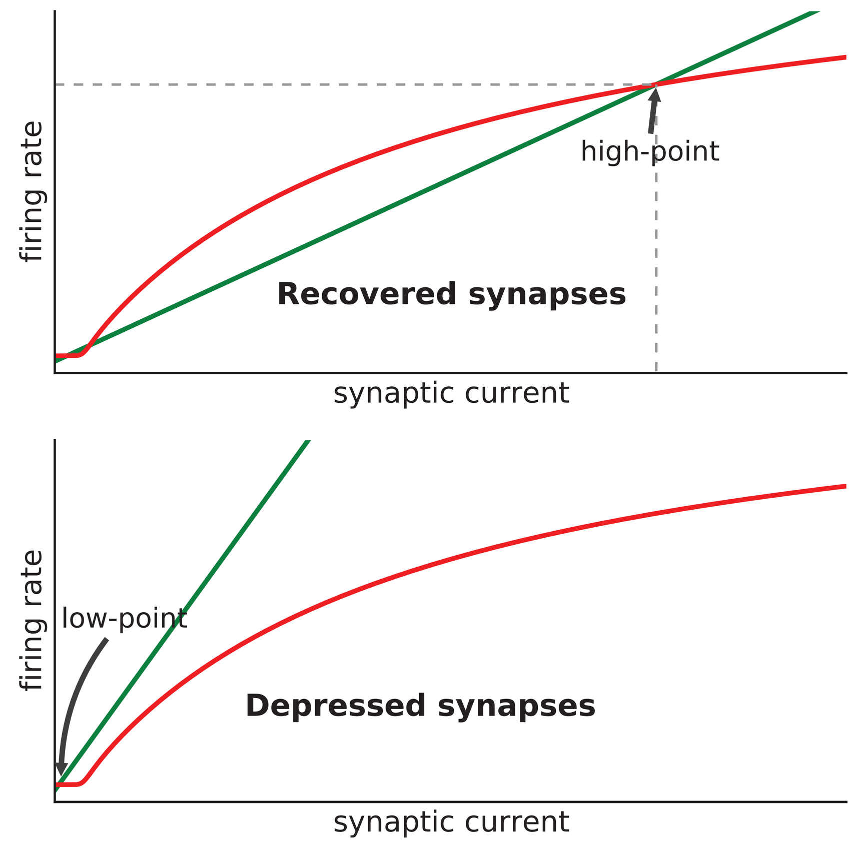
2. Synaptic input (mean field):

$$I_{\mathrm{syn}} = \sum_i w_i\left(\int_{-\infty}^{+\infty}\alpha(s)S_i(t-s)ds\right) \Rightarrow \langle I_{\mathrm{syn}}\rangle = Npq\bar{w}r$$

$$\Rightarrow r = \frac{\langle I_{\mathrm{syn}}\rangle}{Npq\bar{w}}$$

Driving the assembly with small but sufficient input brings it to the "high-point".

During the high-point state, synapses depress ➔ assembly switches to depressed mode and converges to the "low-point".

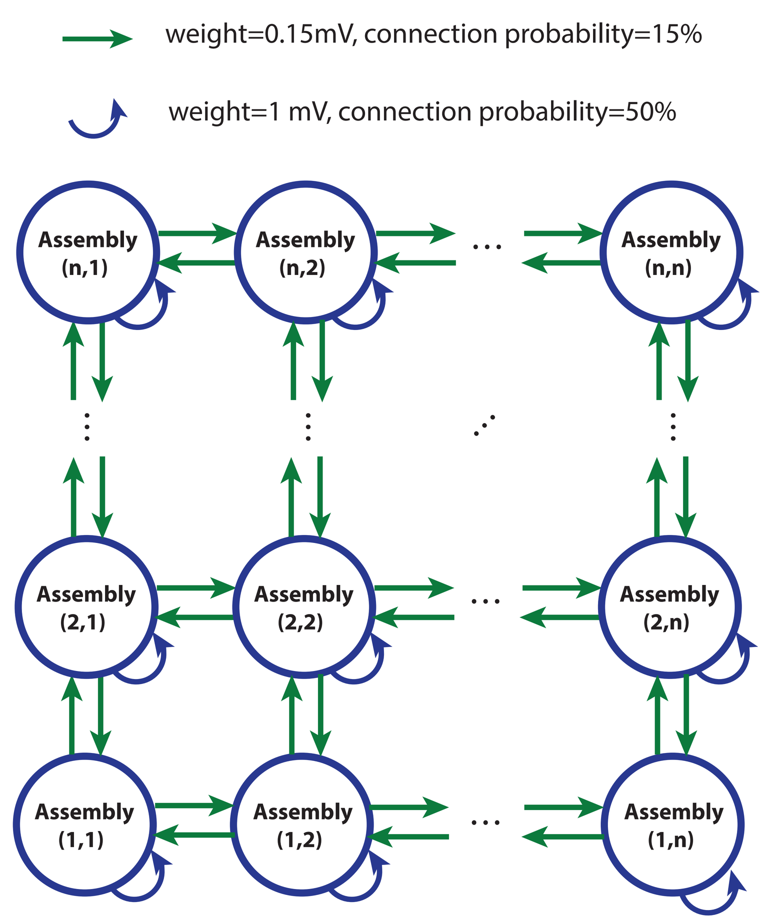


Grid of bistable assemblies

1-dimensional chain of assemblies can be extended to a 2-dimensional topology (grid).

inter assembly connections: Weak synapses, low connection probabiliy

intra-assembly connections: Strong synapses, high connection probability, short-term depression



Can be used for modeling columnar organization of cortex (e.g. barrel cortex): Sparse and weak inter-column synaptic connections versus relativey strong intra-column synapses.

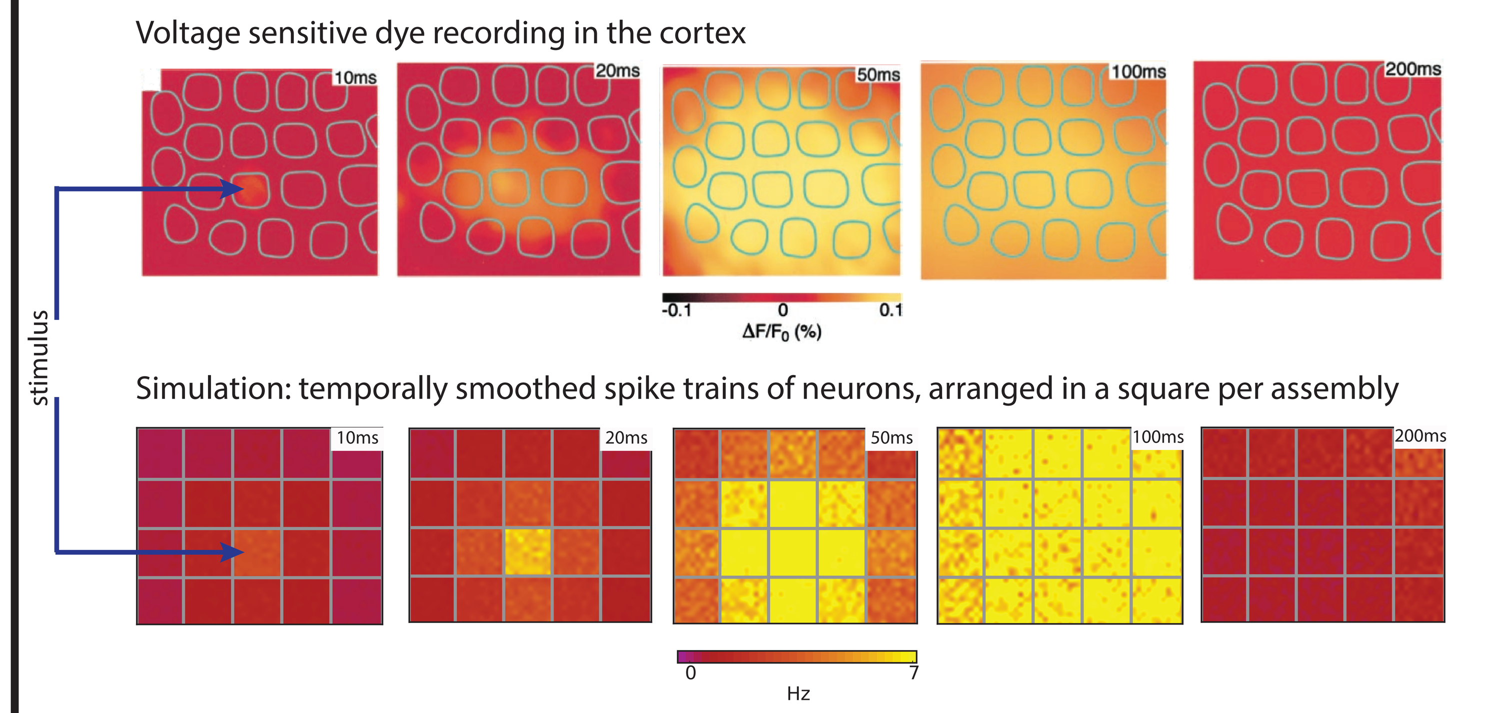
Each cortical column contains ~10K neurons, while each assembly contains 100 neurons!
The model is still valid: A few hub neurons (neurons that receive stronger and more synapses) inside each column may govern its dynamics. Each assembly of the grid can be considered as a population of hub neurons in the column.

Different patterns of activity propagation in the grid

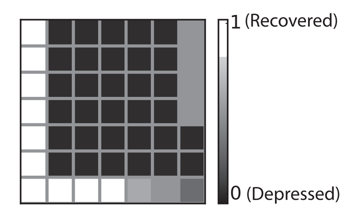
Dynamics of intra-assembly synapses are described by a depression variable x [3]. A high (low) value of x denotes recovered (depressed) synapses. Using different initial values of x for different assemblies, we can evoke different patterns of activity propagation on the grid.

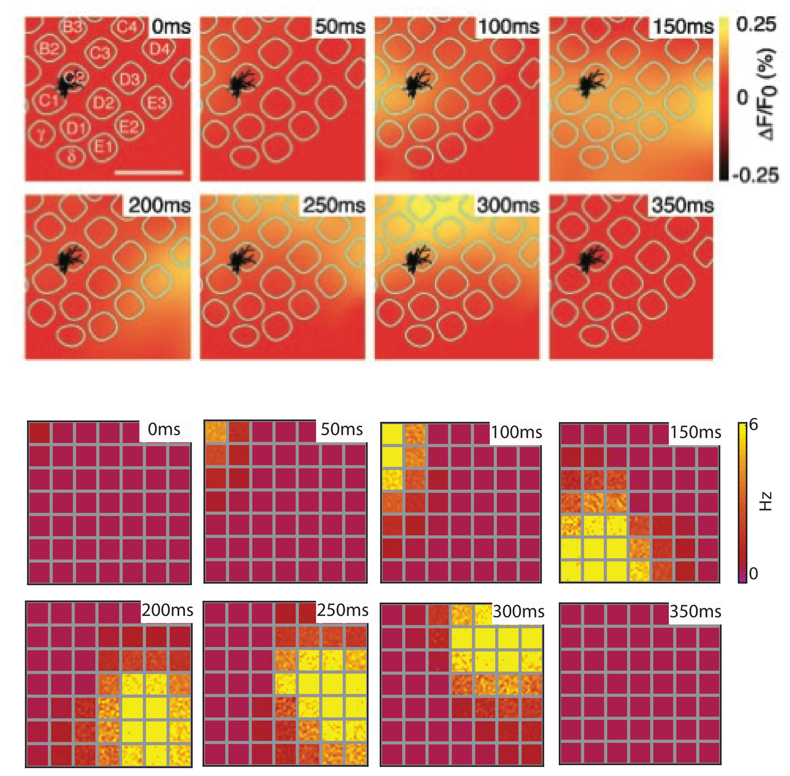
$$\frac{dx}{dt} = \frac{1-x}{\tau_{\mathrm{rec}}} - Ux\delta(t-t_f)$$

Reproducing activity propagation in the barrel cortex after a brief whisker stimulus [6]:



Reproducing activity circulation in the anaesthetised barrel cortex [7] by setting the initial values of x:





The activity can circulate forever or stop after several rounds based on inter-assembly synaptic weights.
Relatively strong synapses guarantee enough excitation for the next assemblies in the trajectory, while very weak synapses cause activity to vanish.

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Funding

Research was supported by the European Research Council (grant agreement no. 268 689, H.S.), the European Community's Seventh Framework Program (Grant Agreement no. 269921, BrainScaleS, H.S and M.D.) and the Swiss National Science Foundation (grant agreement no. 200020_147200, M.D.).