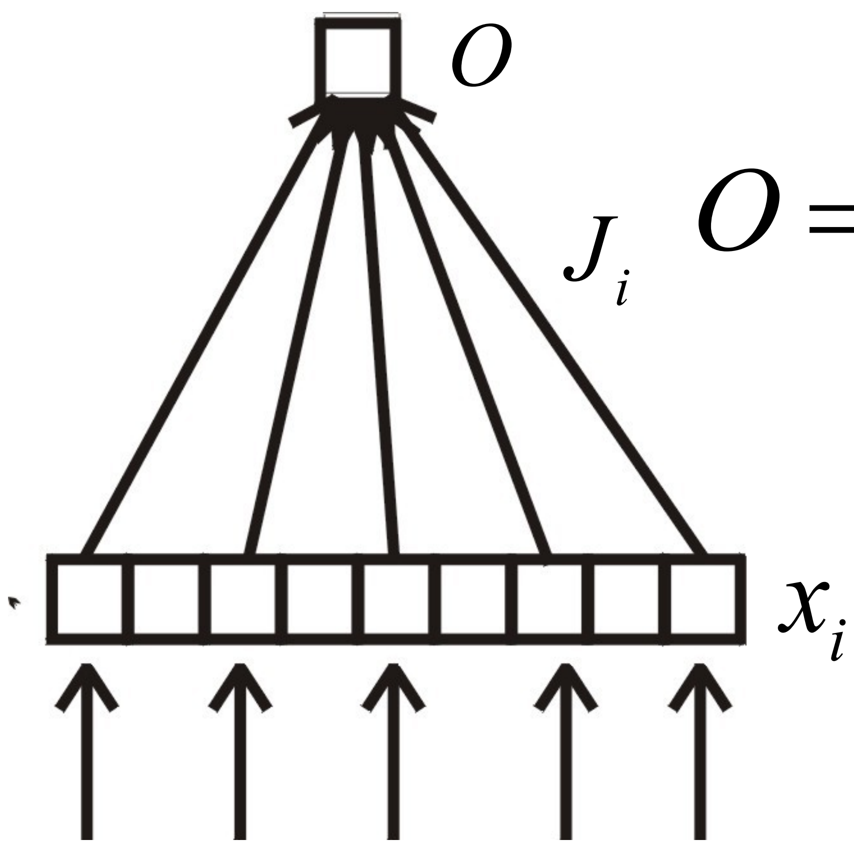
Information Processing in Cortical Neural Networks with Dynamic Synaptic Connections

Misha Tsodyks
Weizmann Institute of Science

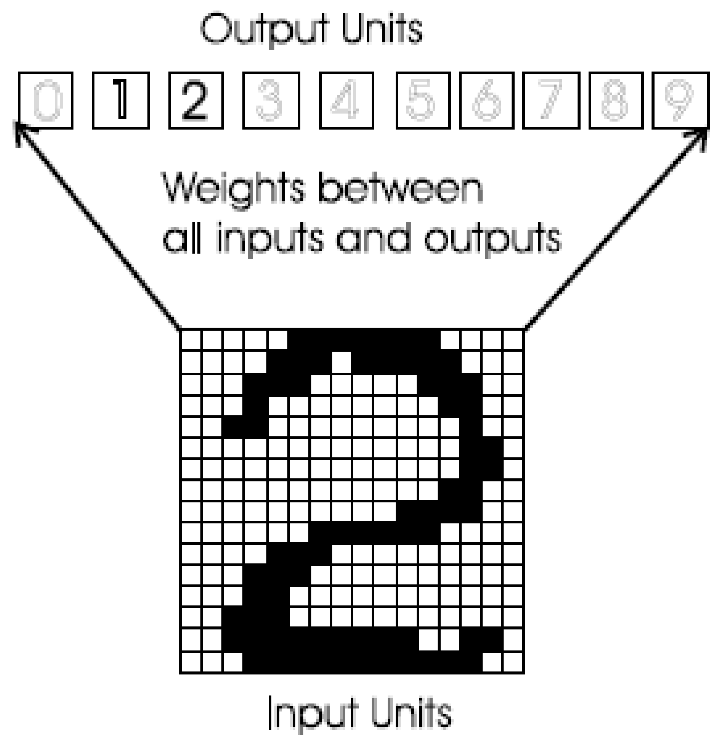
Complexity in Jerusalem 2008

Feed-forward networks: Perceptron

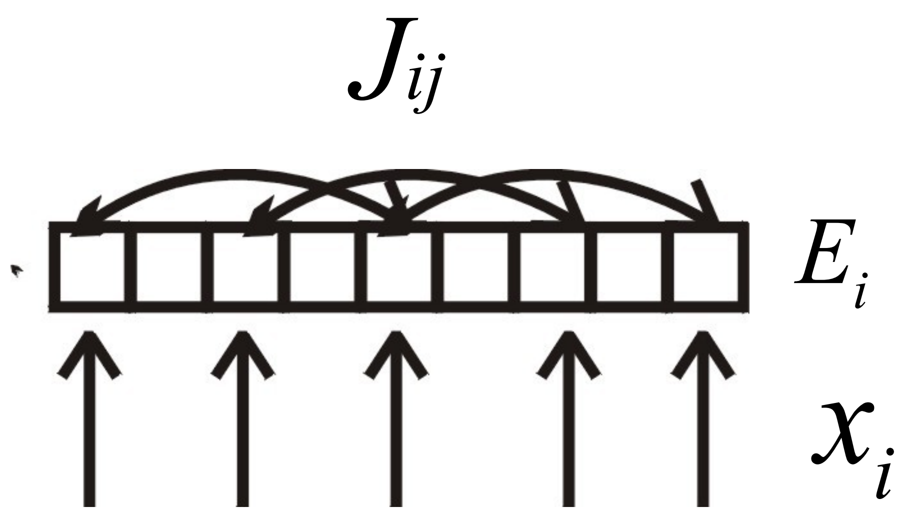


$$O = sign(\sum_i J_i x_i - T)$$

Simple network

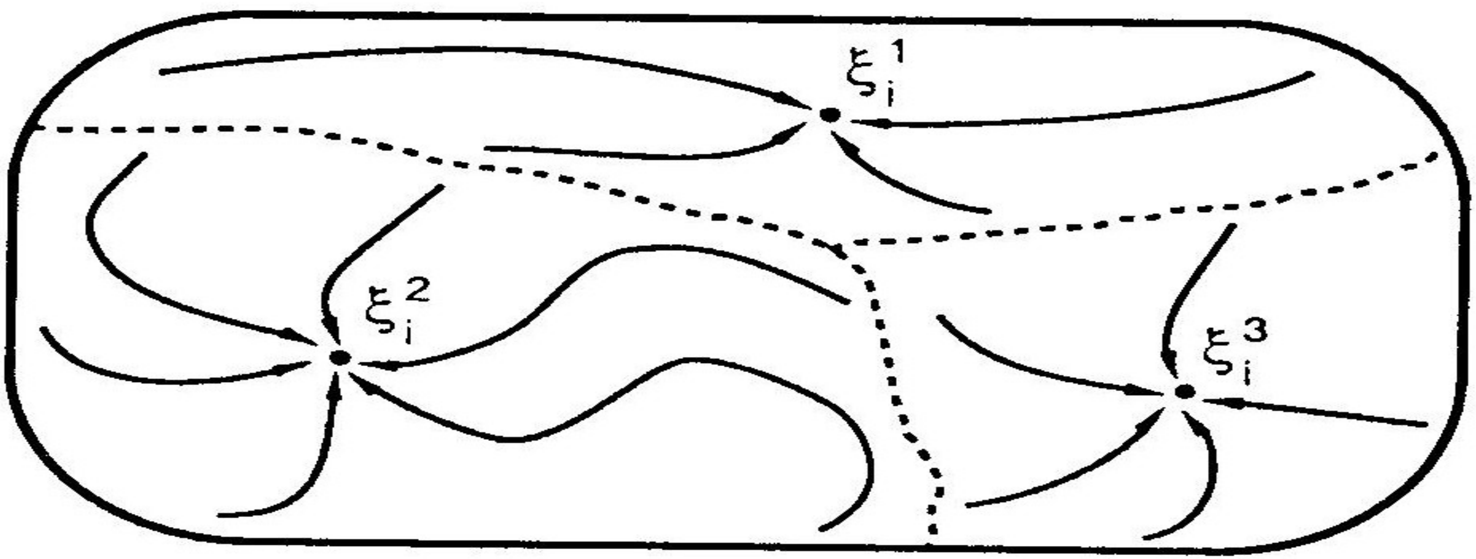


Recurrent networks

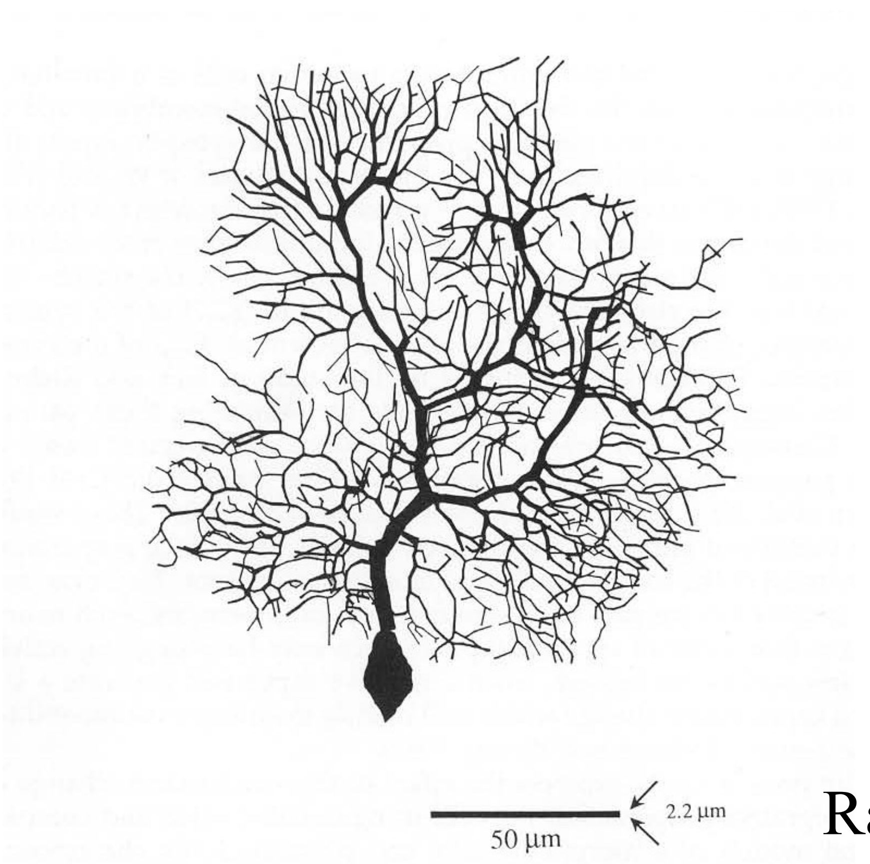


$$\tau \dot{E}_i = -E_i + g\left(\sum_j J_{ij} E_j + x_i\right)$$

Memory patterns as network attractors

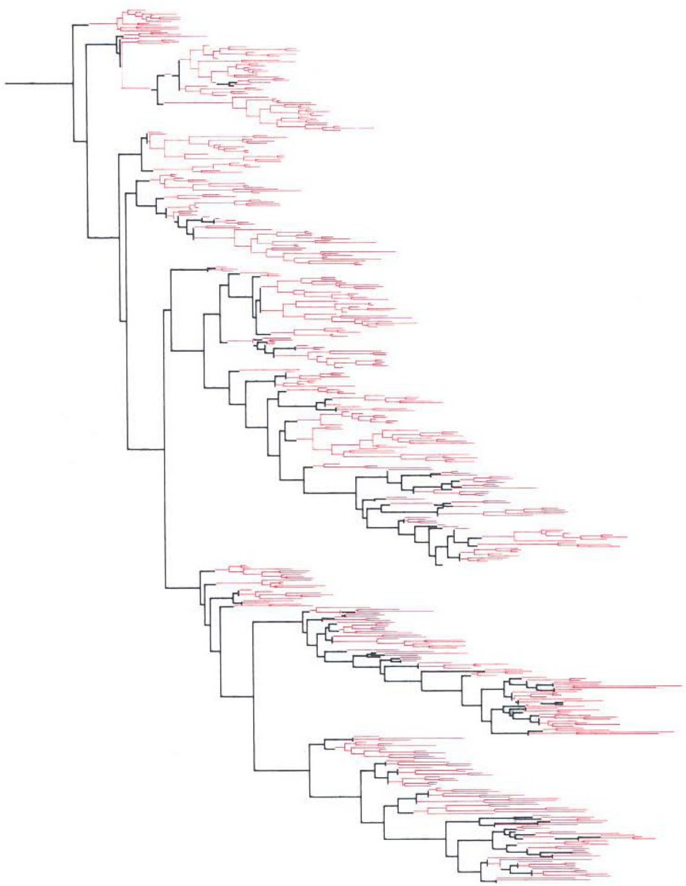


Purkinje cell reconstruction

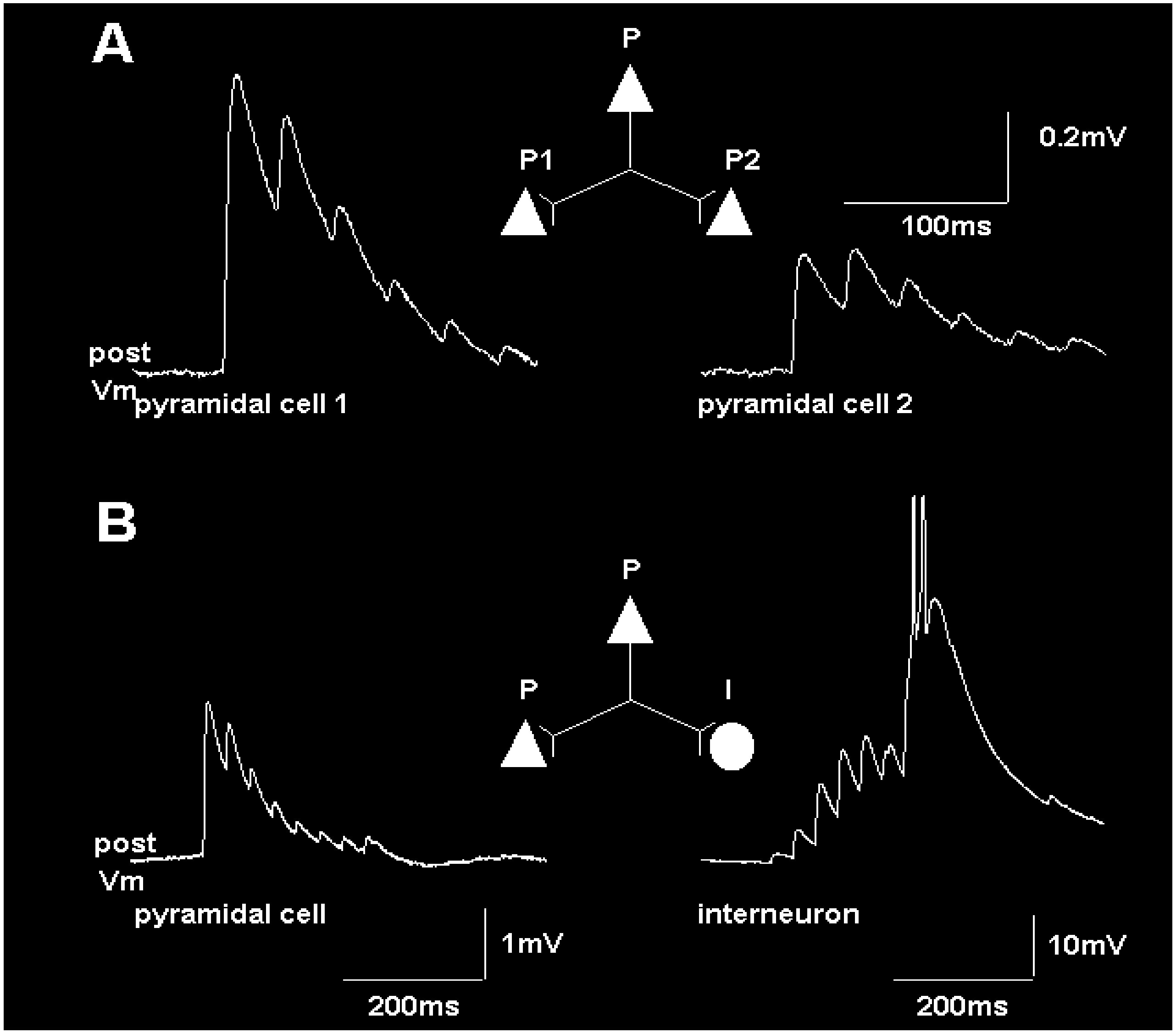


Rapp, Yarom & Segev 1992

Multi-compartment modelling



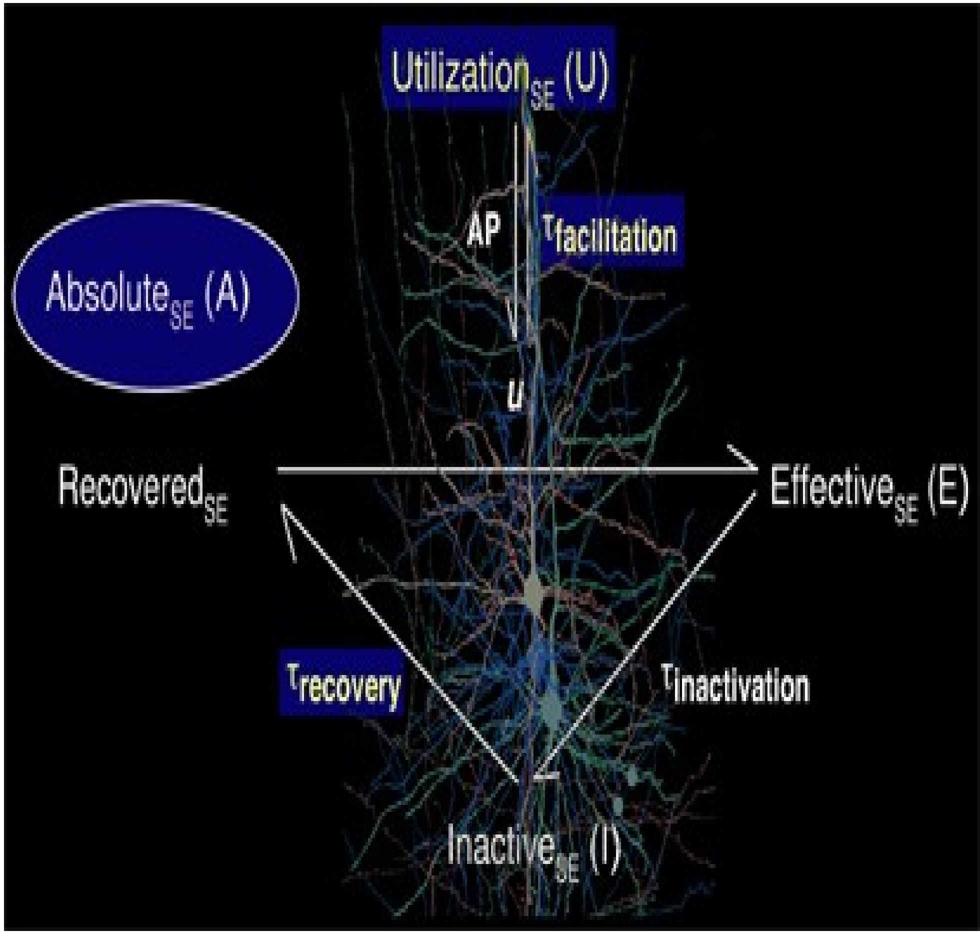
Short-term Synaptic Plasticity



Markram, Wang & Tsodyks 1998

A Phenomenological Approach to Dynamic Synaptic Transmission

- **4 Key Synaptic Parameters**
  - Absolute strength
  - Probability of release
  - Depression time constant
  - Facilitation time constant



Markram, Wang & Tsodyks 1998

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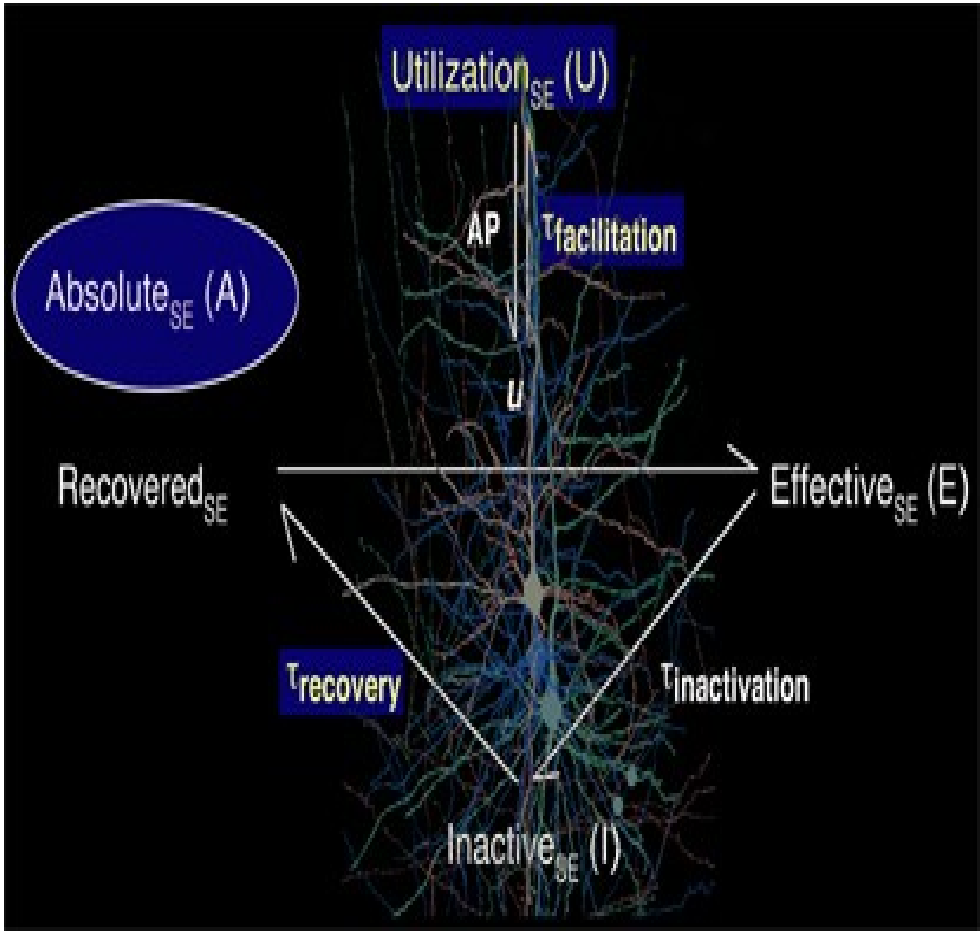
- **2 Synaptic Variables**
  - Resources available (x)
  - Release probability (u)



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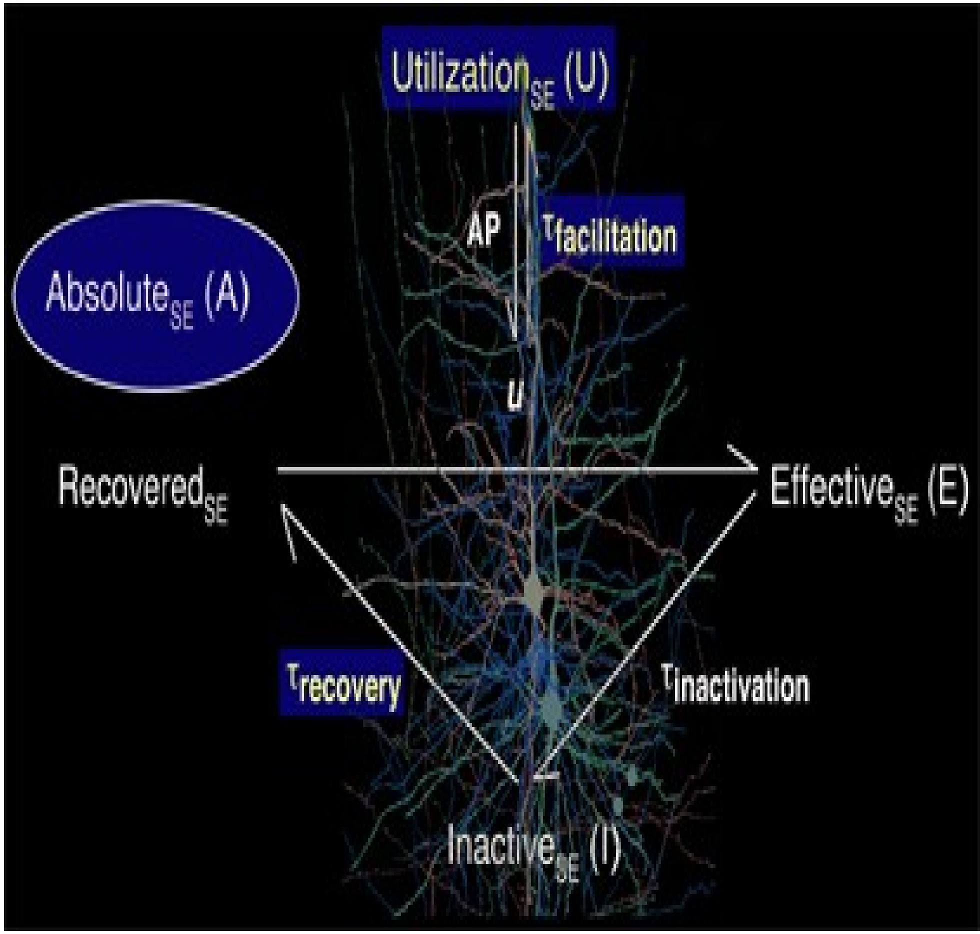
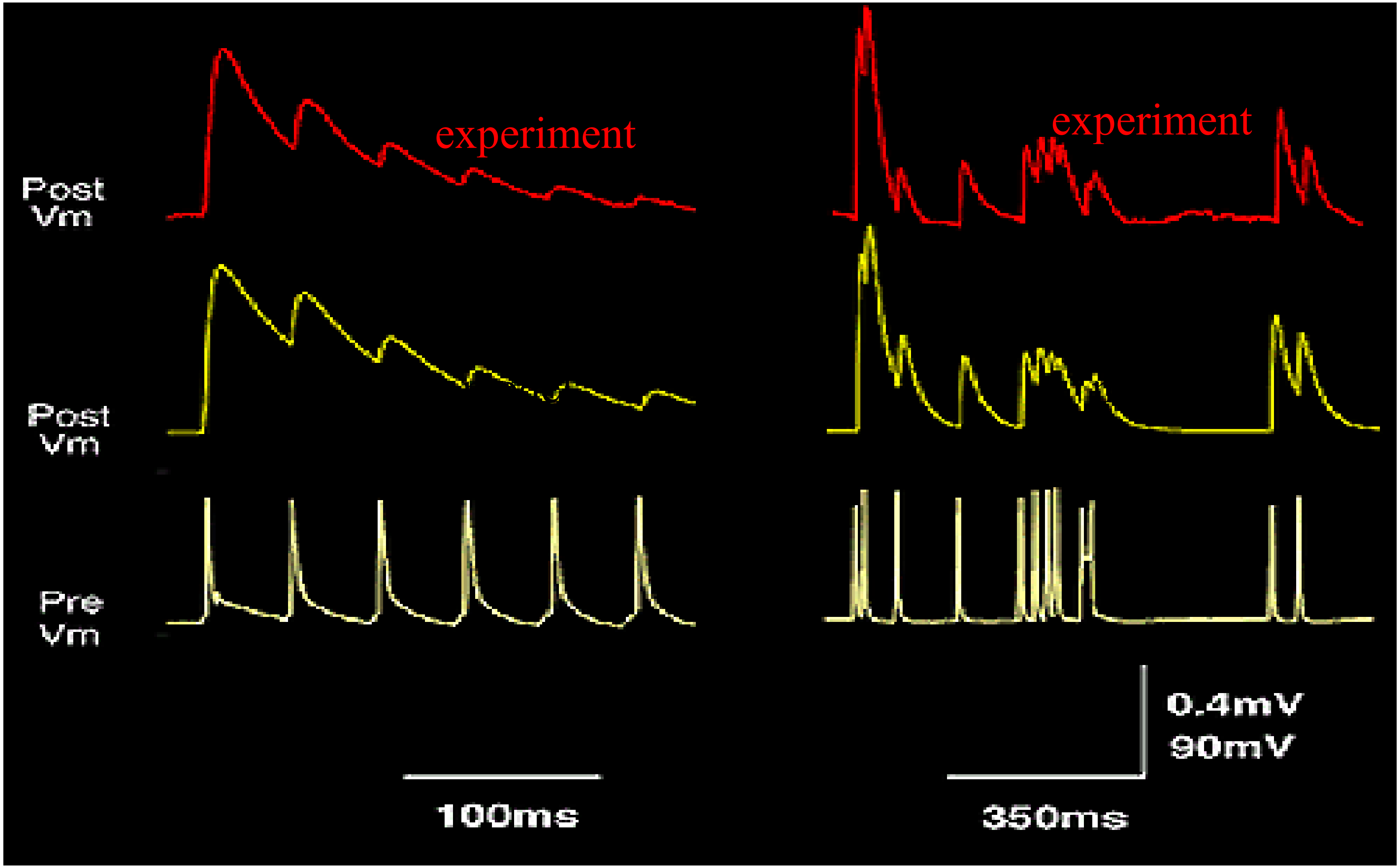
$$\frac{du}{dt} = -\frac{u-U}{\tau_f} + U(1-u)\delta(t-t_{sp})$$

$$\frac{dx}{dt} = \frac{1-x}{\tau_d} - ux\delta(t-t_{sp})$$



Markram, Wang & Tsodyks 1998

Testing the Model: Depressing Synapses



Tsodyks & Markram 1997

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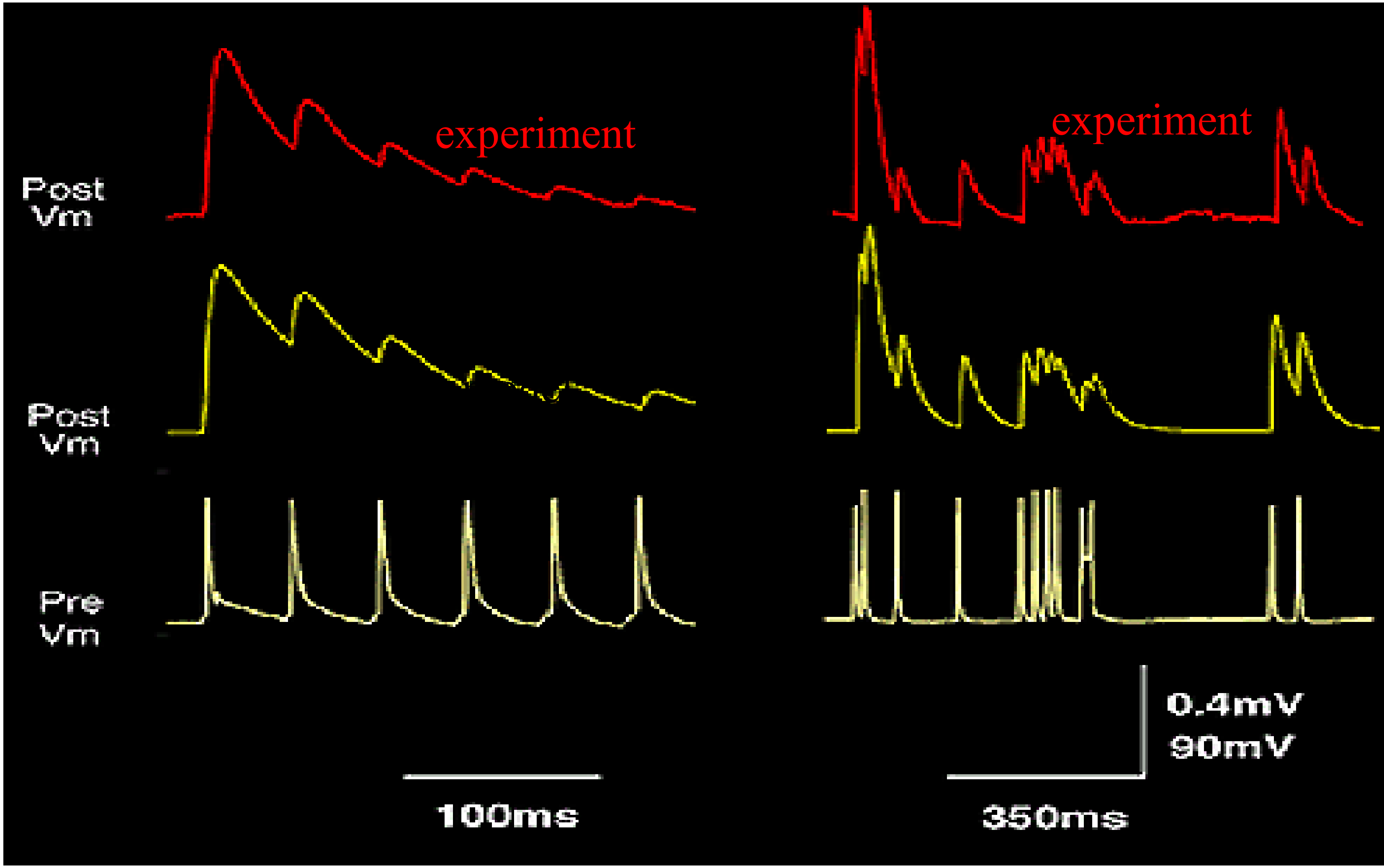
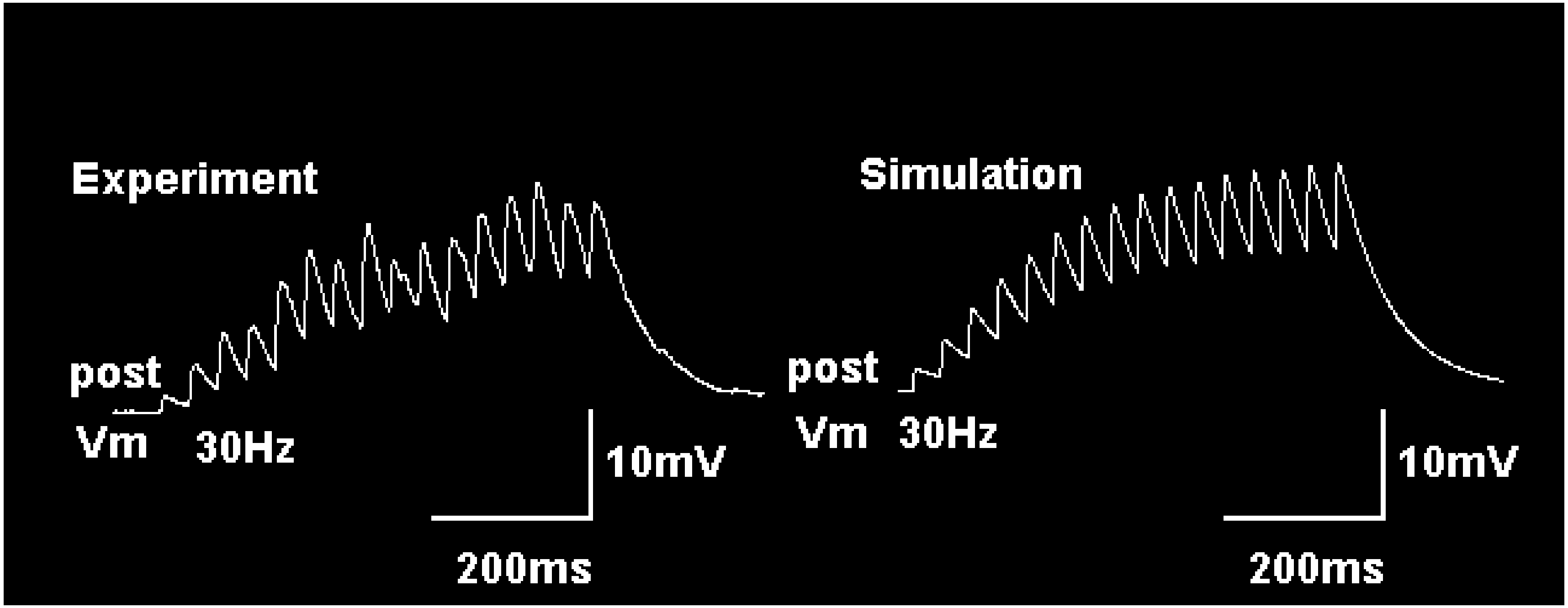


$$U \approx 0.5 \quad \tau_d \approx 1\text{sec} \quad \tau_f \to 0$$

Facilitation ($\tau_f >> \tau_d$)



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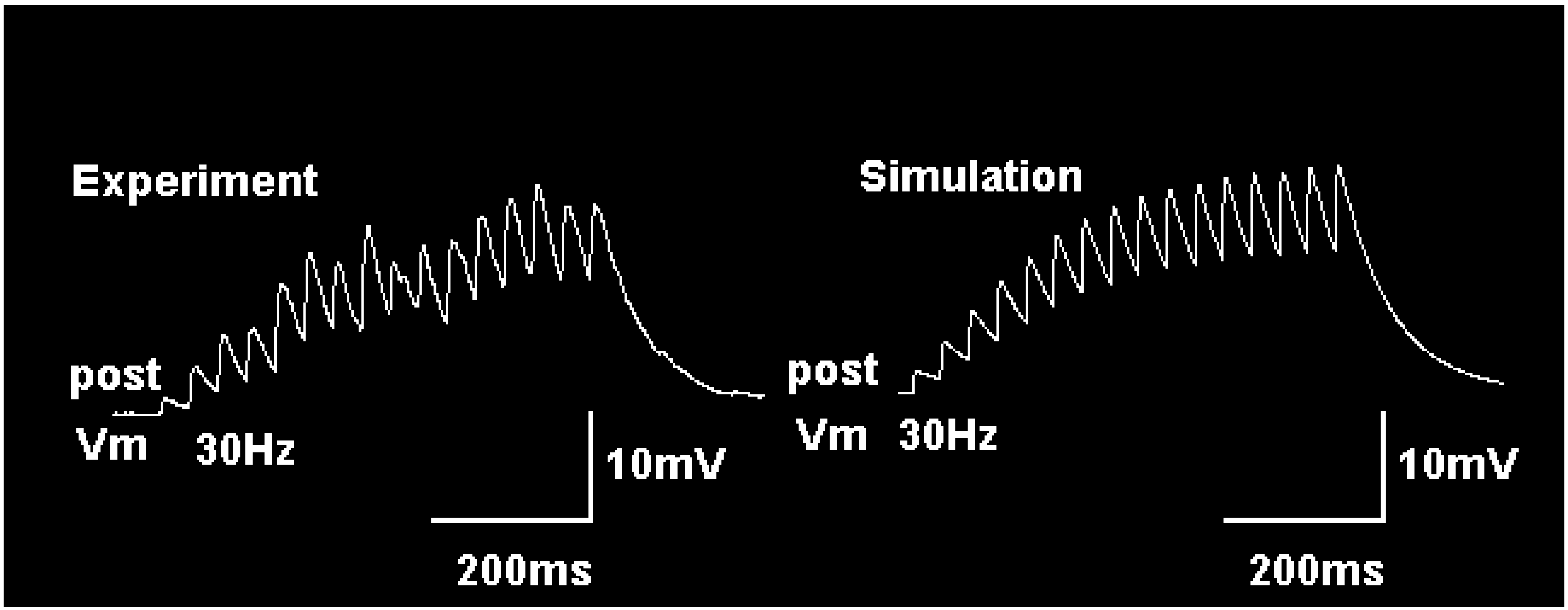
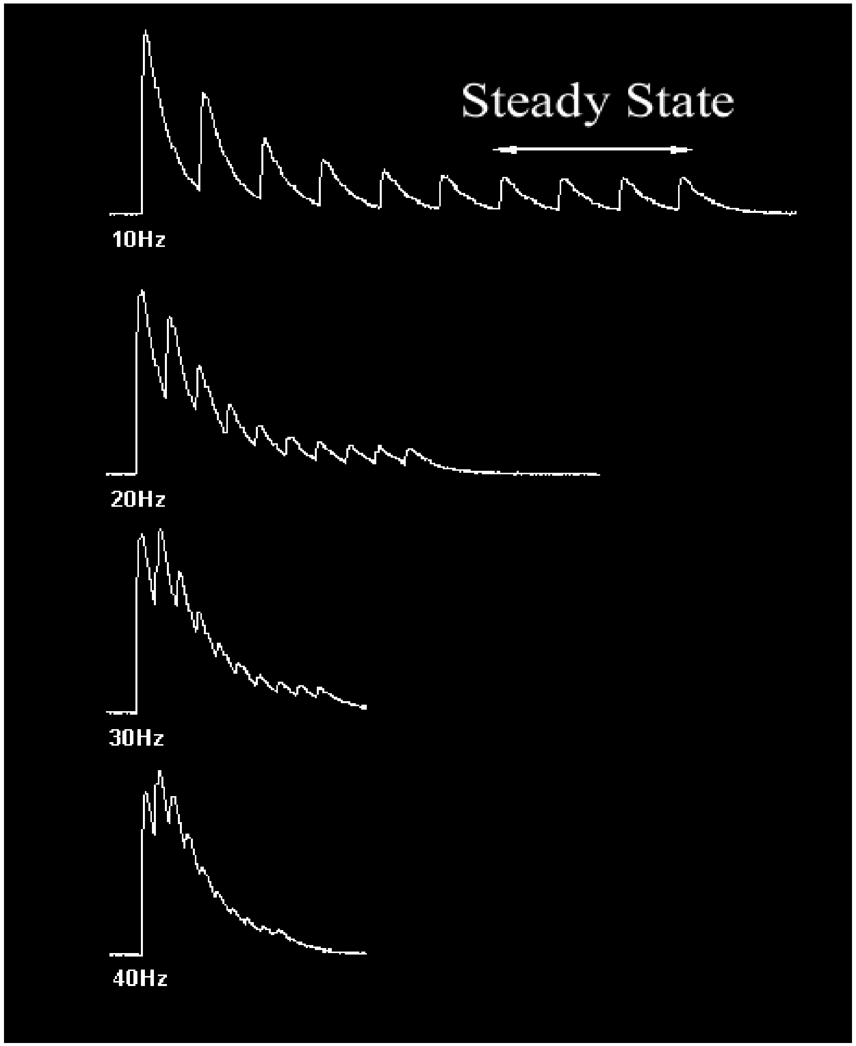
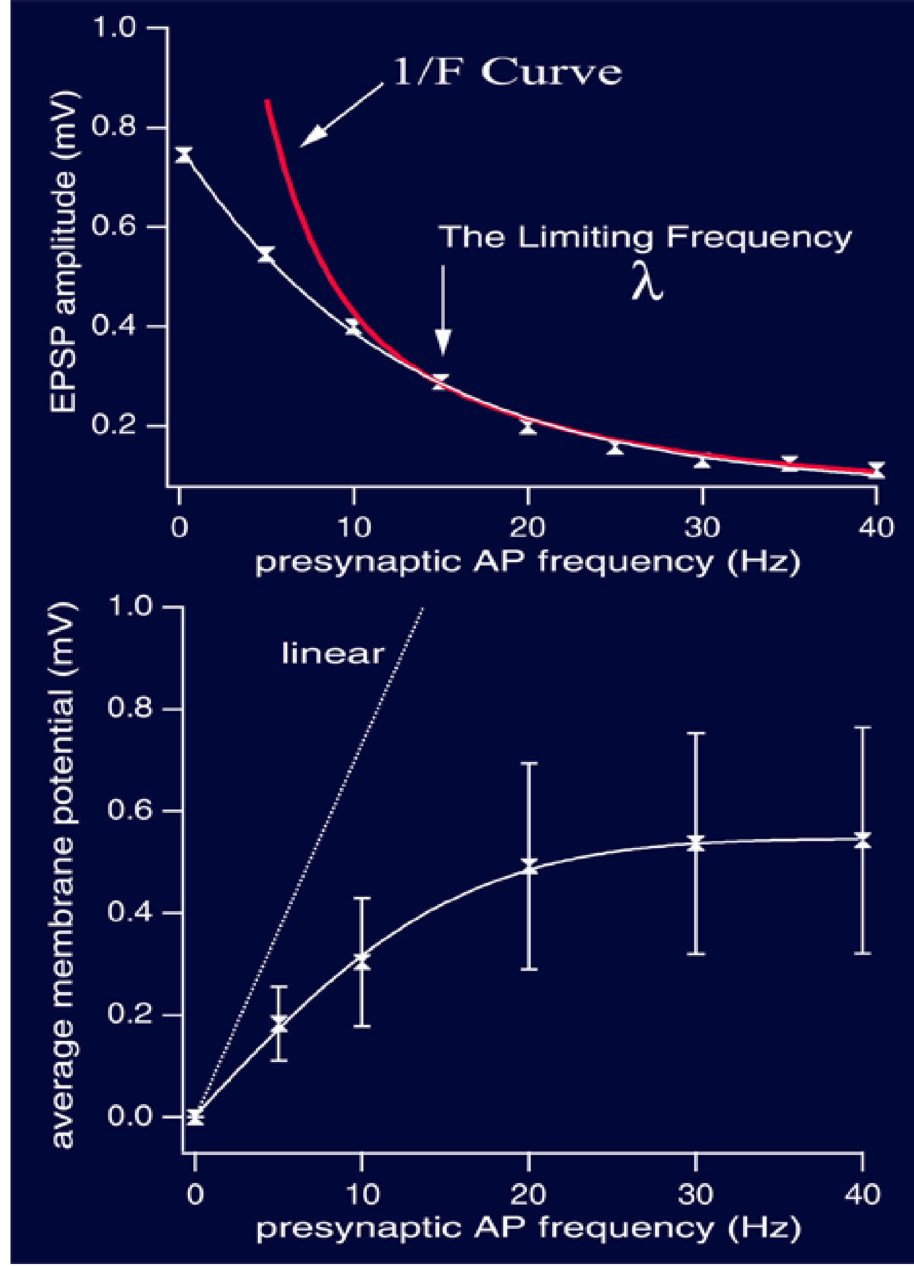


$$U \square 0.1 \quad \tau_d \square 0.1\mathrm{sec} \quad \tau_f \square 1\mathrm{sec}$$

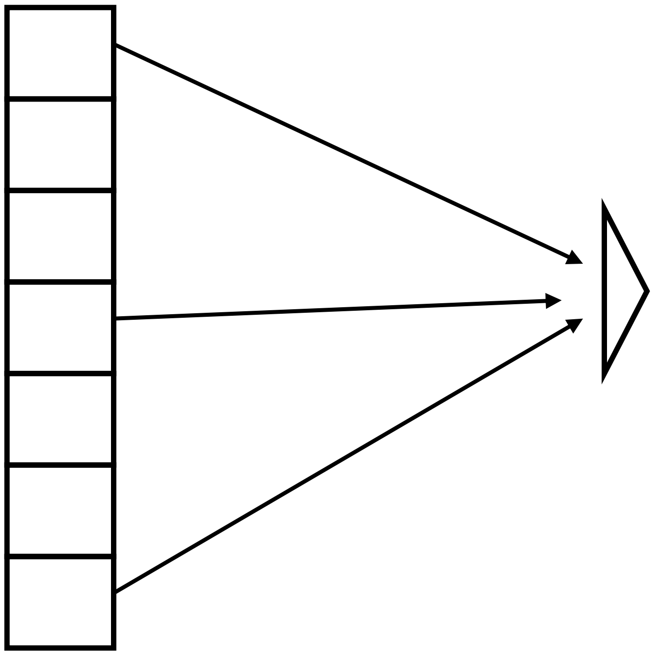
The 1/f Law of Release



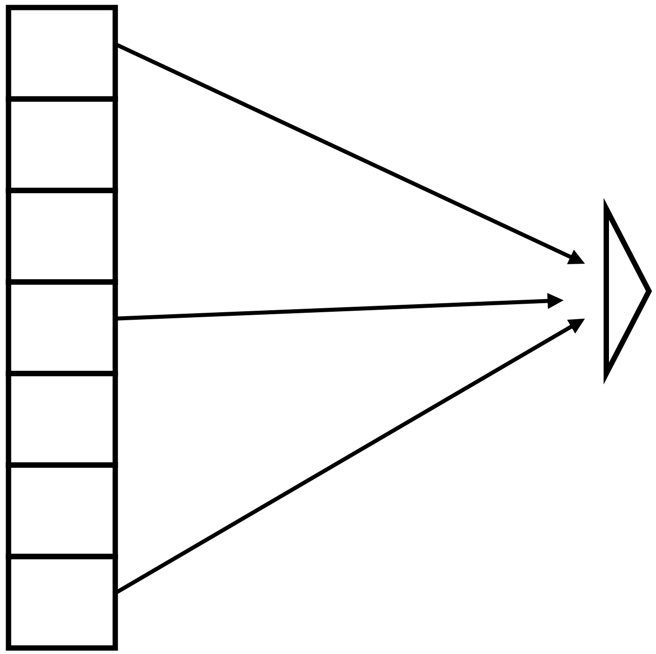


Abbott et al 1997, Tsodyks & Markram 1997

Synaptic depression and neural signalling

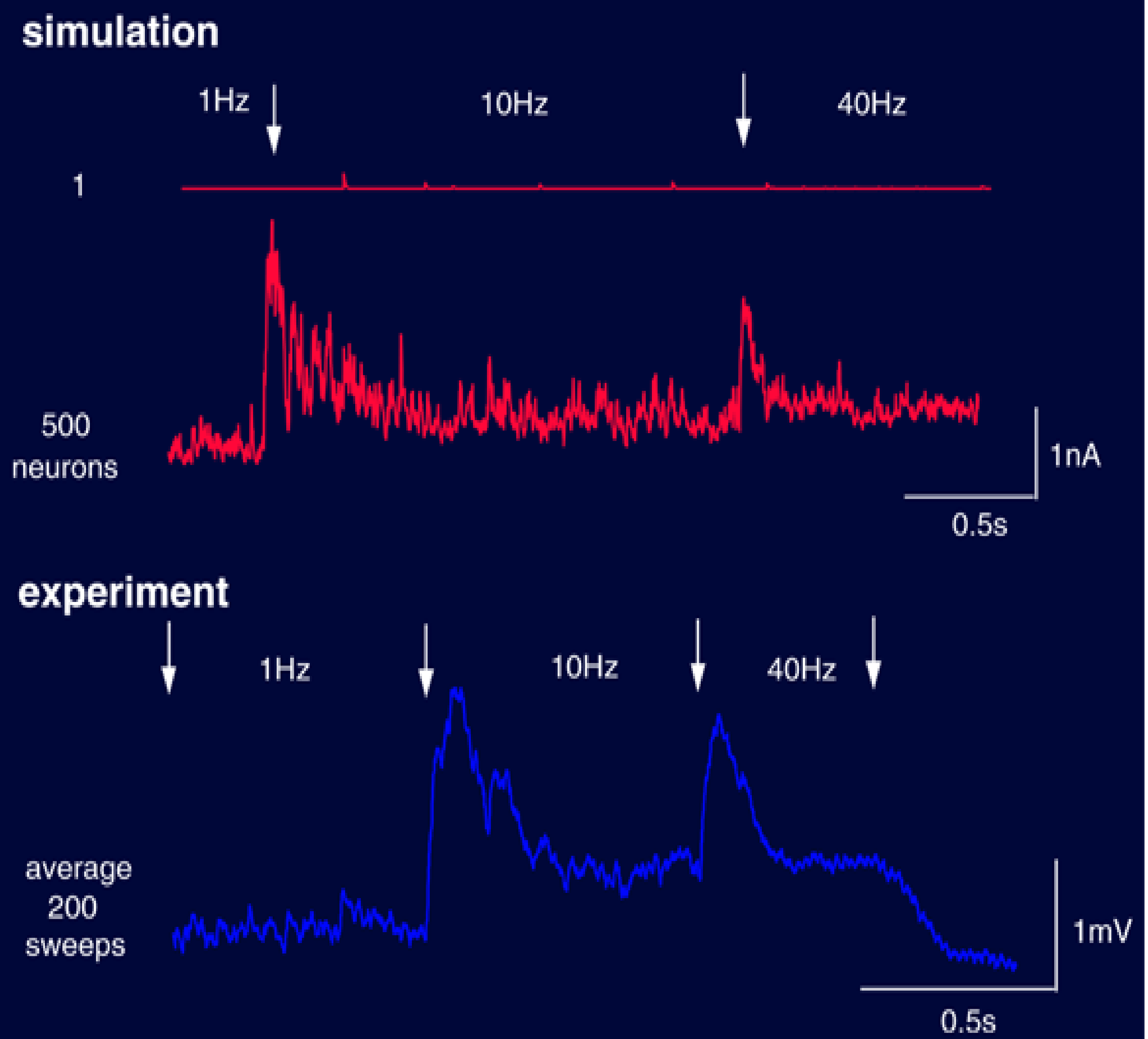


Synaptic depression and neural signalling



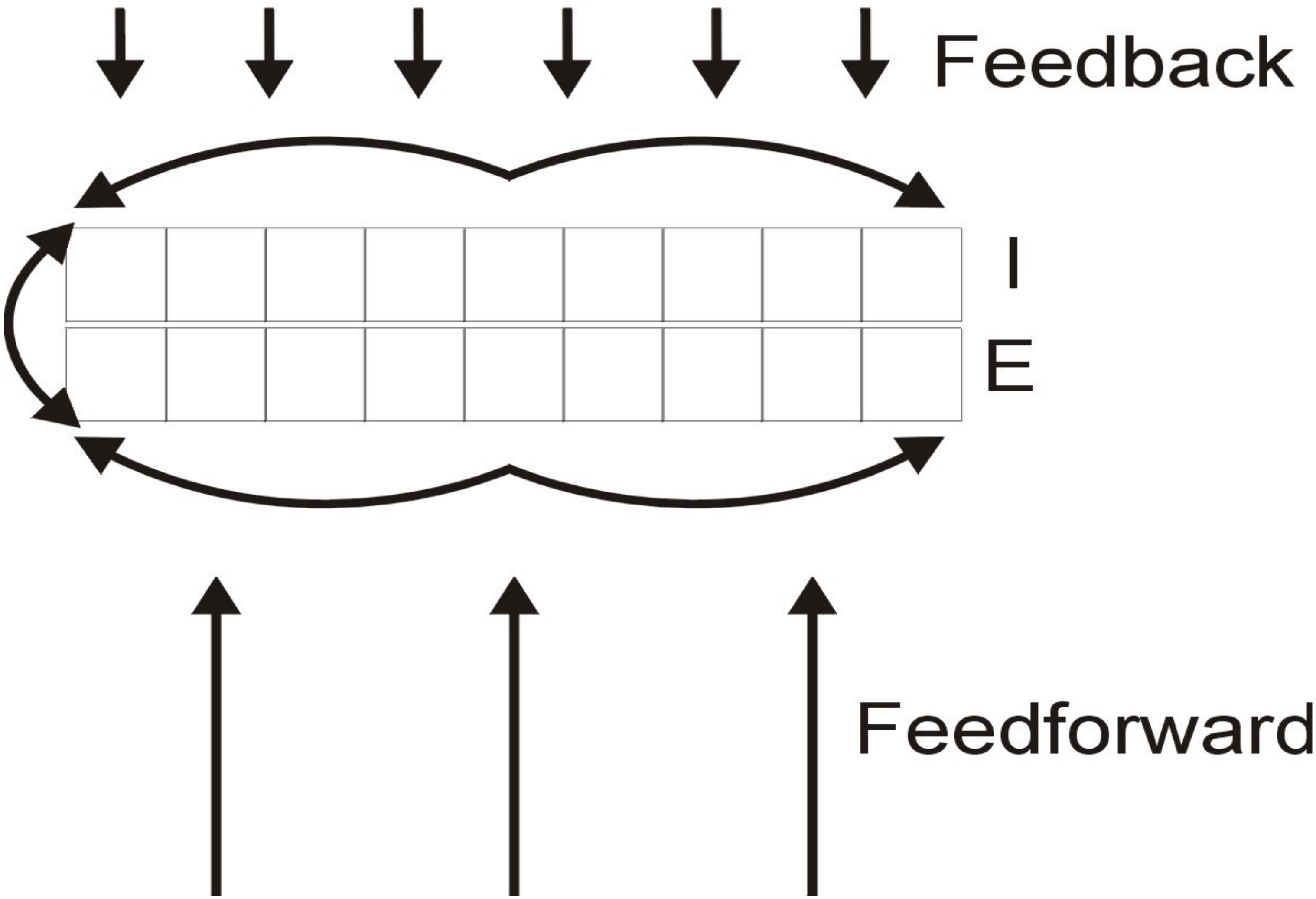
Spiking activity -> Synaptic current

Emergence Of A Transient Signal



Recurrent networks with synaptic depression

The Model



Integrate and fire model of a spiking neuron

Dynamics of a membrane voltage

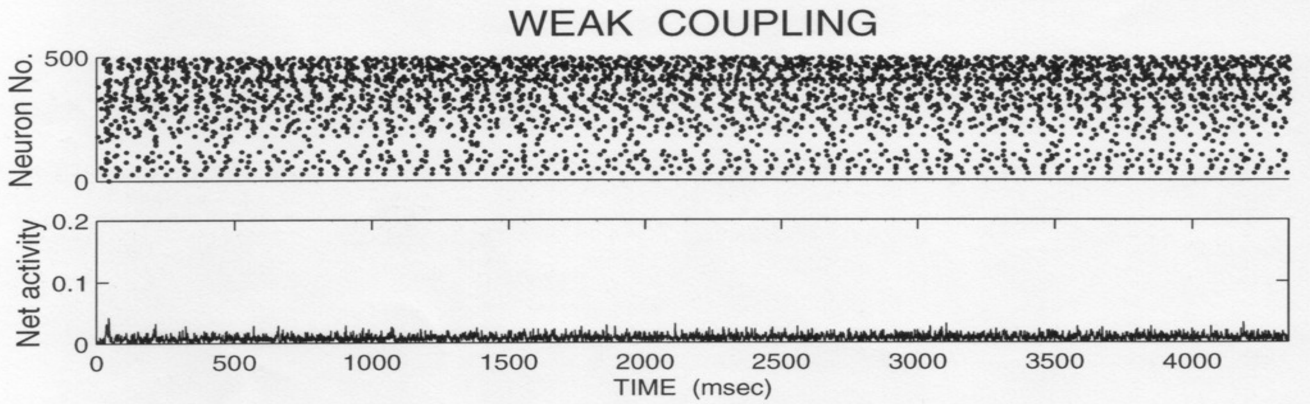
$$\tau \dot{V} = -V + R_{in} I_s$$

Threshold: if $V(t) = \Theta$, A spike has occurred

Reset: $V(tsp+0) = V_{reset}$

Synaptic current: $I_s(t) = \sum_{sp} i_s(t - t_{sp})$

Simulation of Network Activity



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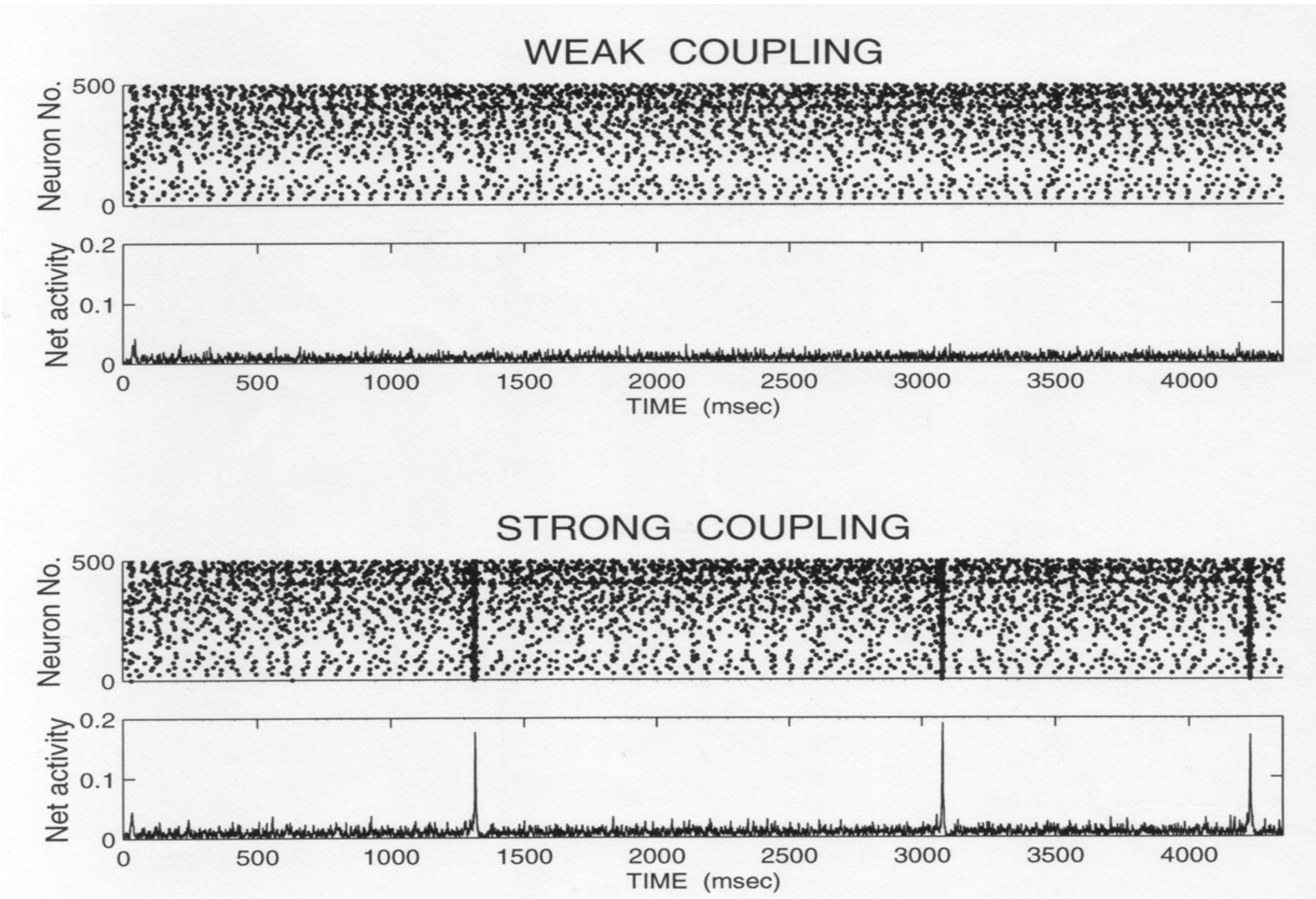
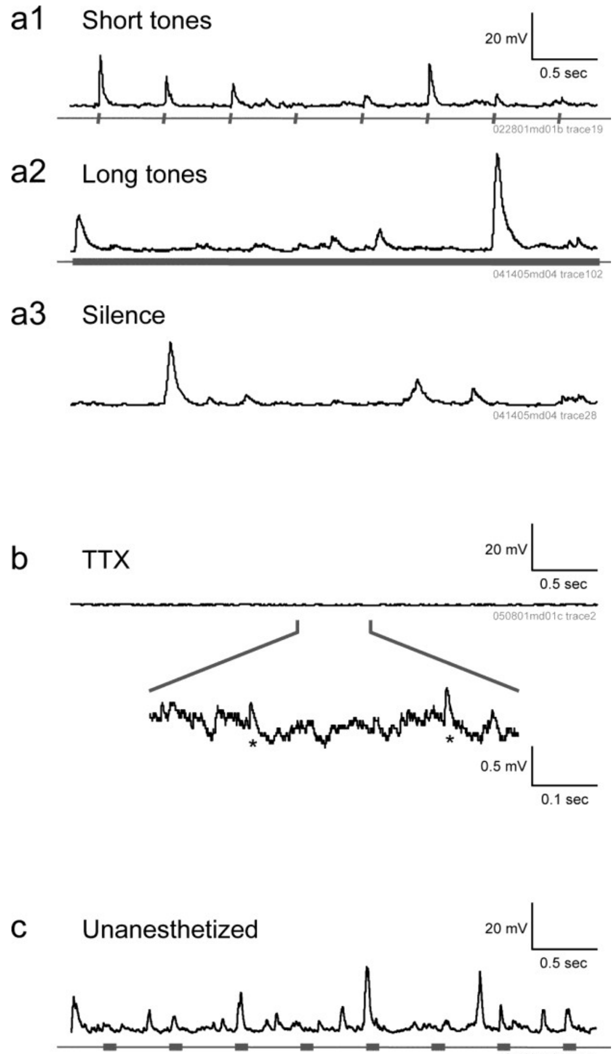


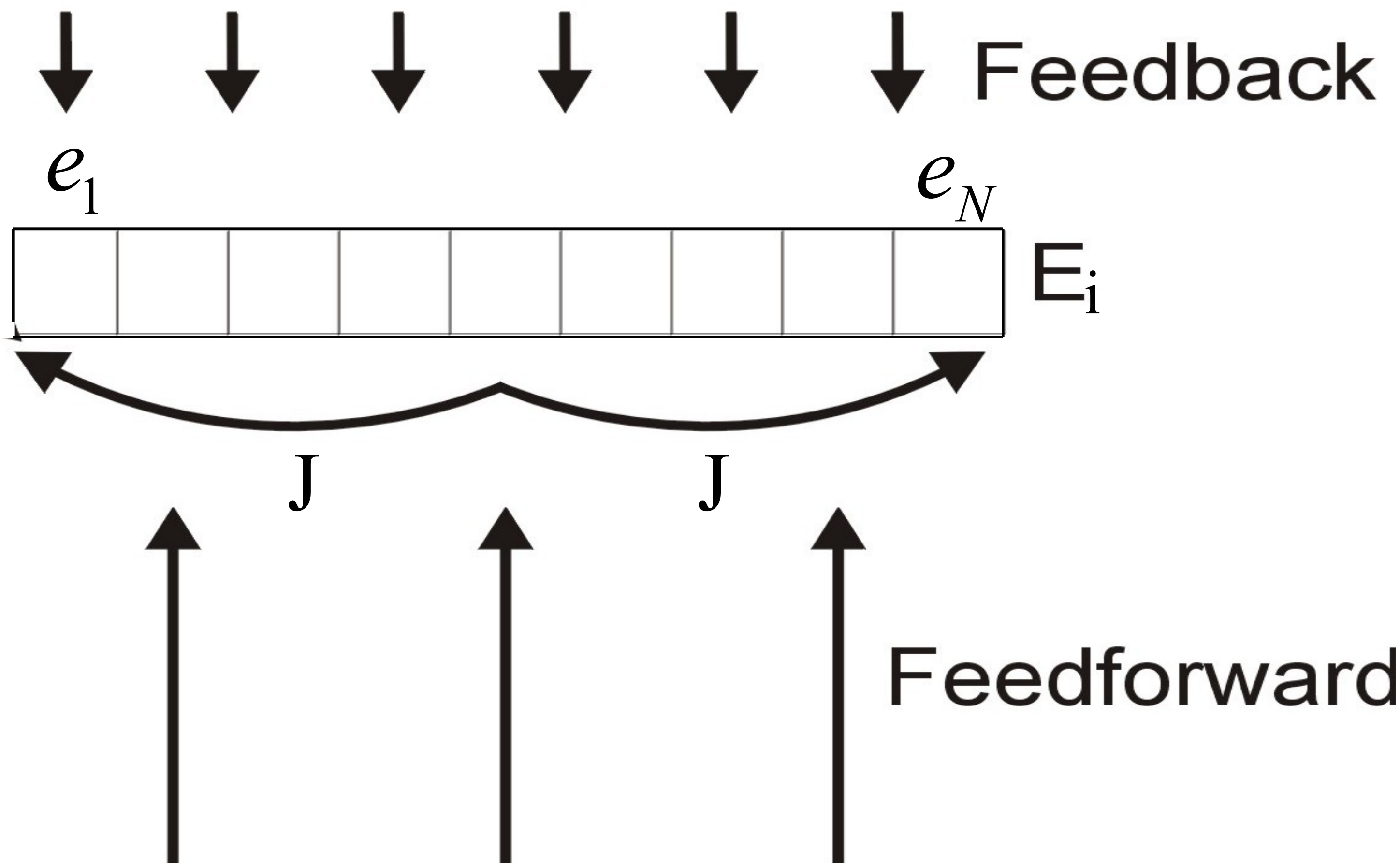
Tsodyks, Uziel & Markram 2000

Experimental evidence for population spikes



DeWeese & Zador 2006

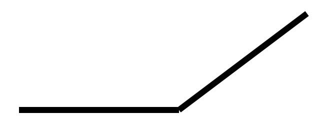
Simplified model
(no inhibition, uniform connections, rate equations)



The rate model equations

- There are two sets of equations representing the excitatory units firing rate, E , and their depression factor, x :

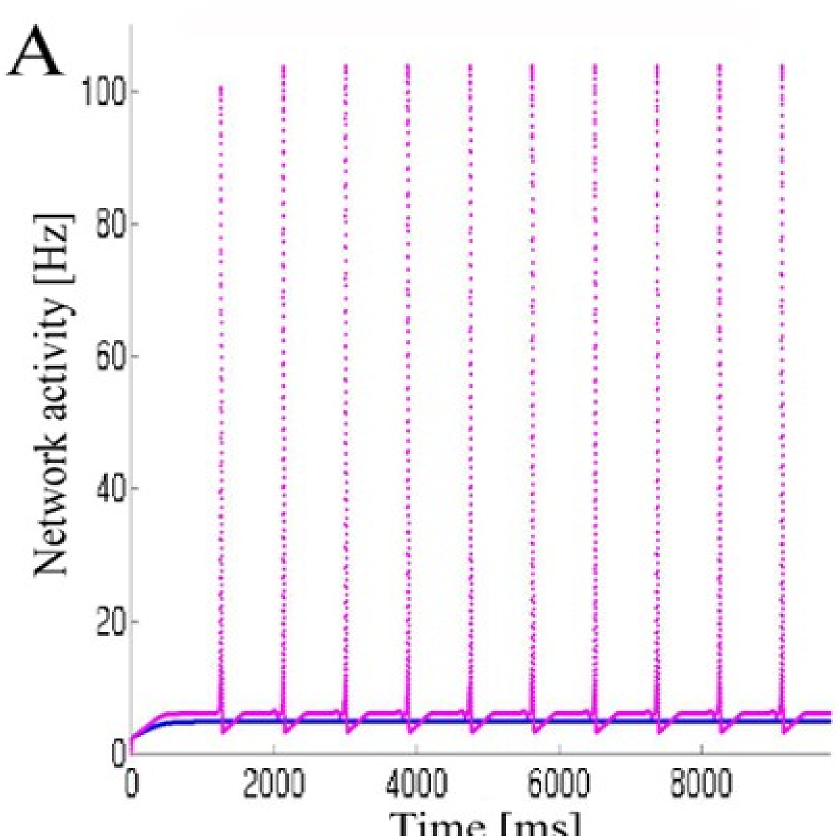
$$\tau \frac{dE_i}{dt} = -E_i + \left[\frac{J}{N}\sum_{j=1}^{N} E_j x_j + e_i\right]_+$$



$$\frac{dx_i}{dt} = \frac{1-x_i}{\tau_r} - u x_i E_i$$

Loebel & Tsodyks 2002

Bifurcation

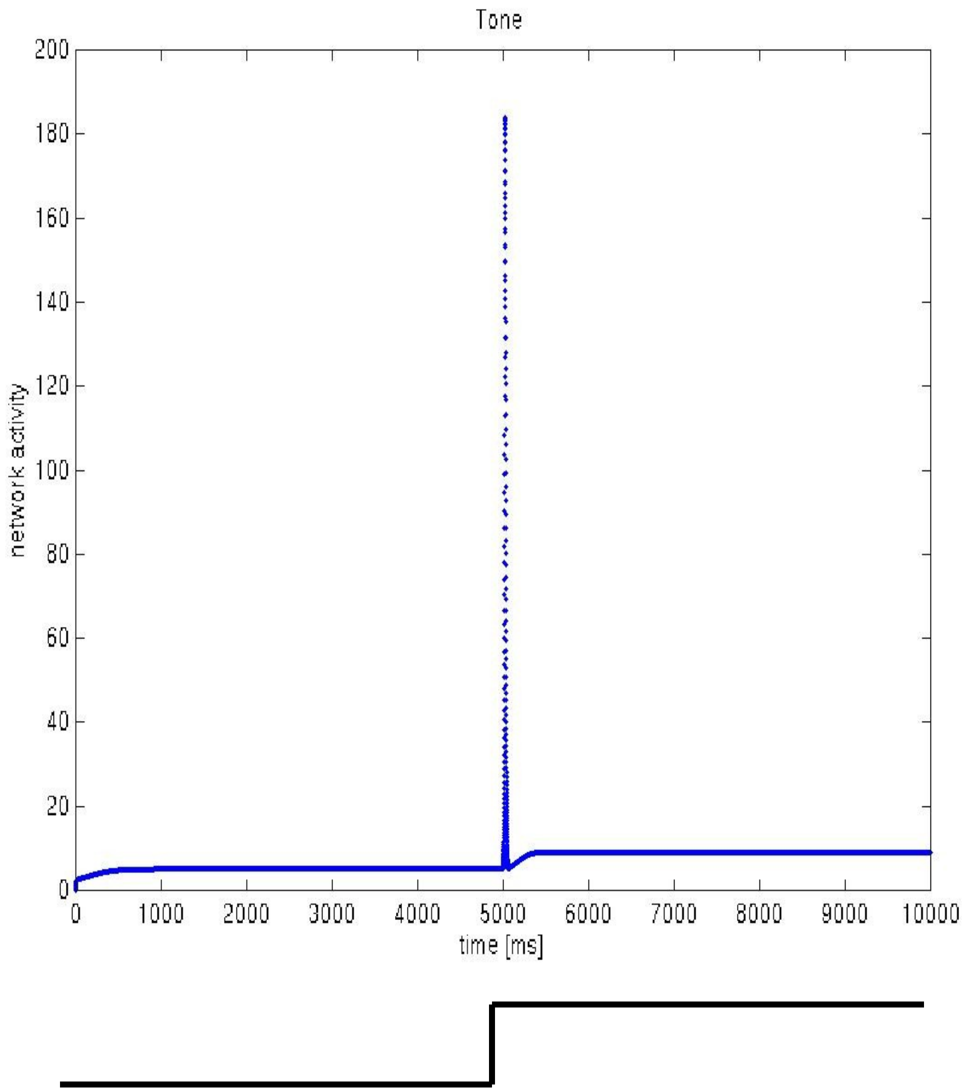


$J < J_{cr}$

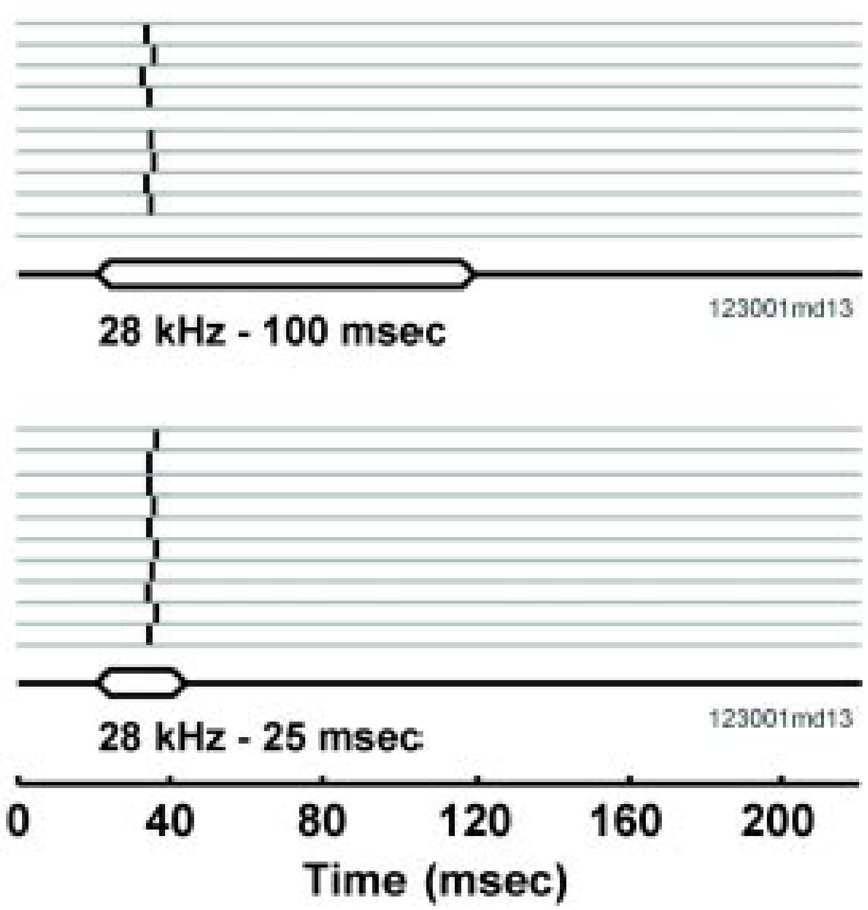
$J > J_{cr}$

Tonic input

The tonic stimuli is represented by a constant shift of the {e}’s, that, when large enough, causes the network to spike and reach a new steady state

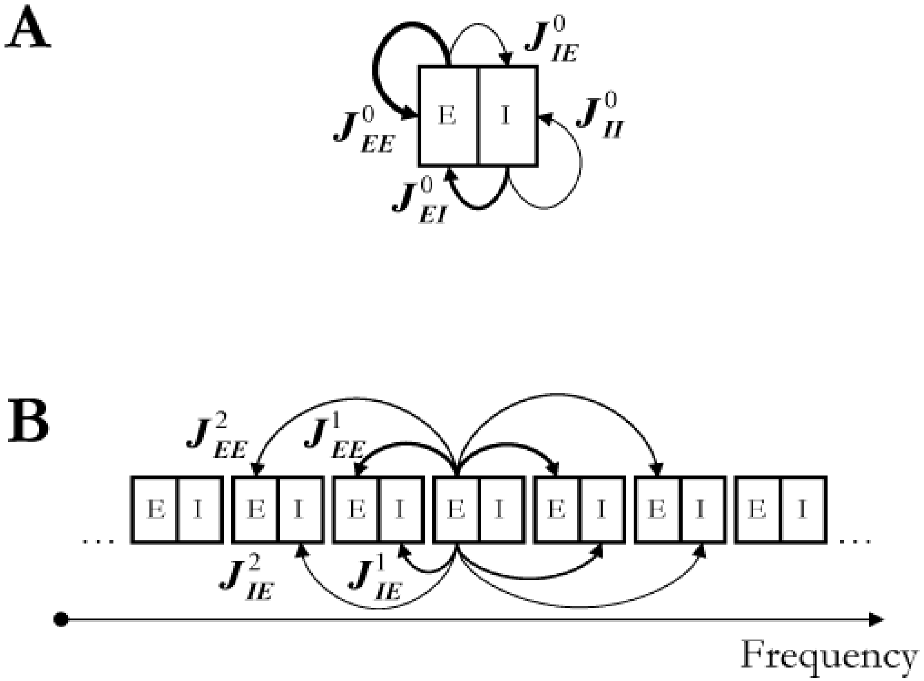


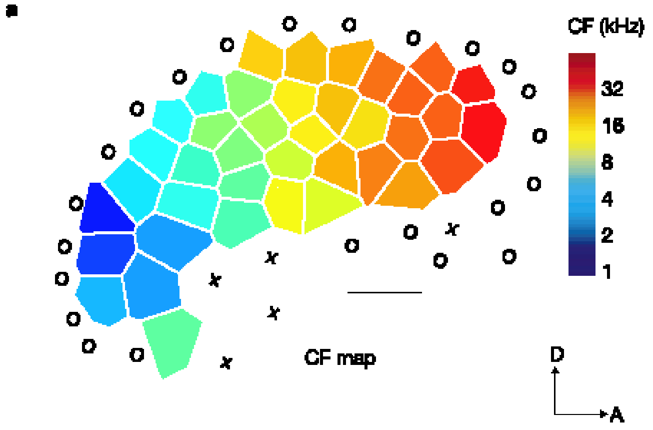
Response of A1 neurons to tonic sounds



DeWeese et al J. Neurosci. 2003

Extended model – A1

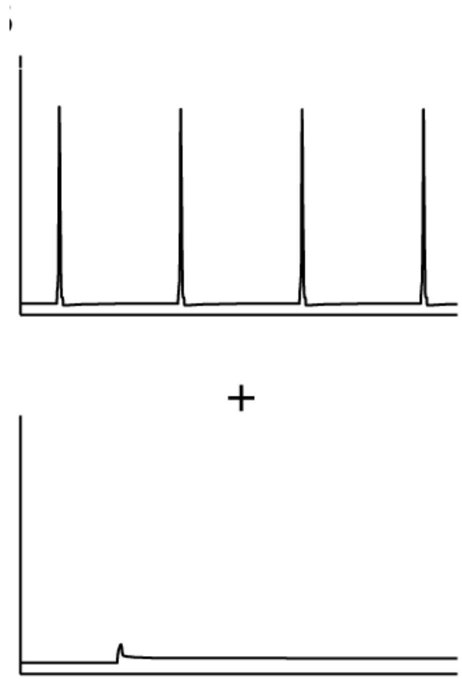




Loebel, Nelken & Tsodyks 2007

Hyper-sensitive locking suppression

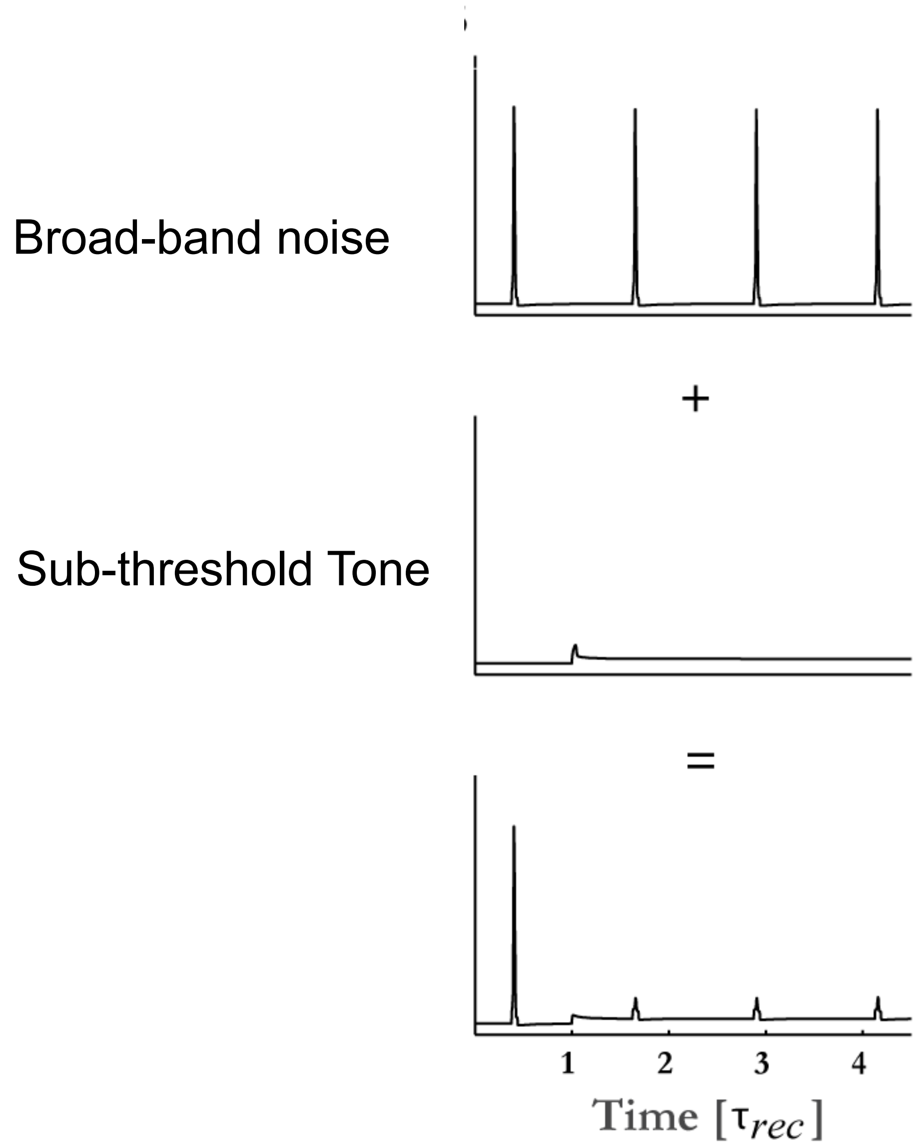
Broad-band noise



+

Sub-threshold Tone

Hyper-sensitive locking suppression



Hyper-sensitive locking suppression

Broad-band noise

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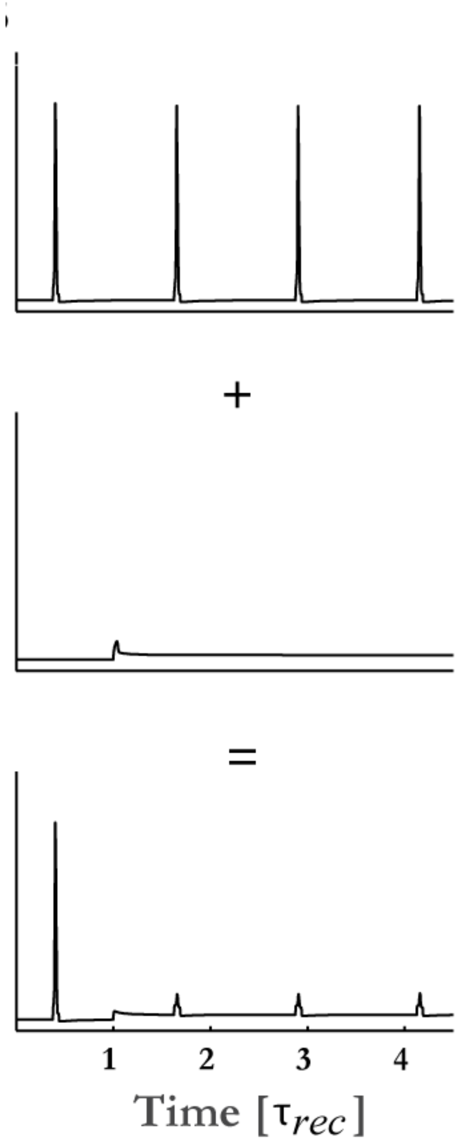
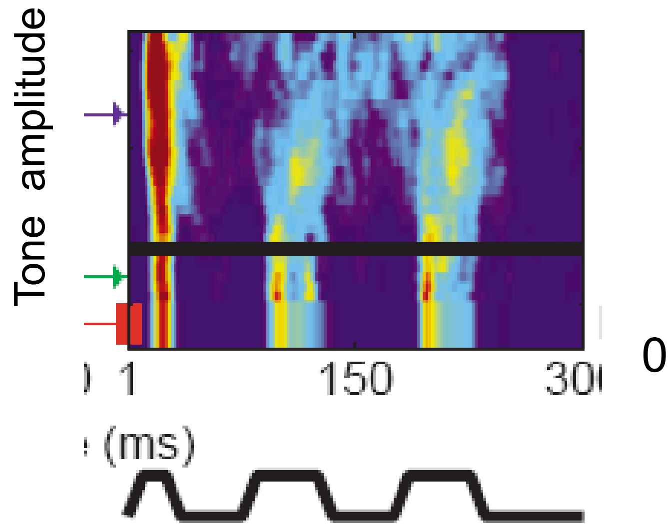
Sub-threshold Tone

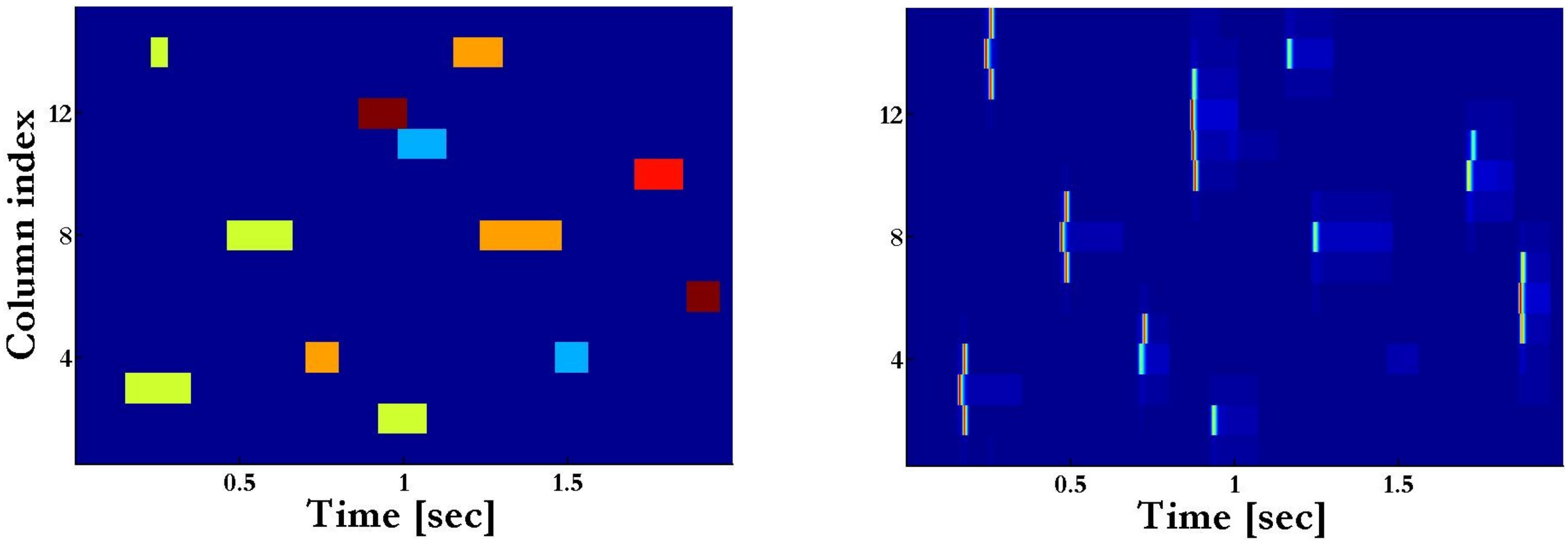
=





(Nelken et al, Nature 1999)

Network response to complex stimuli



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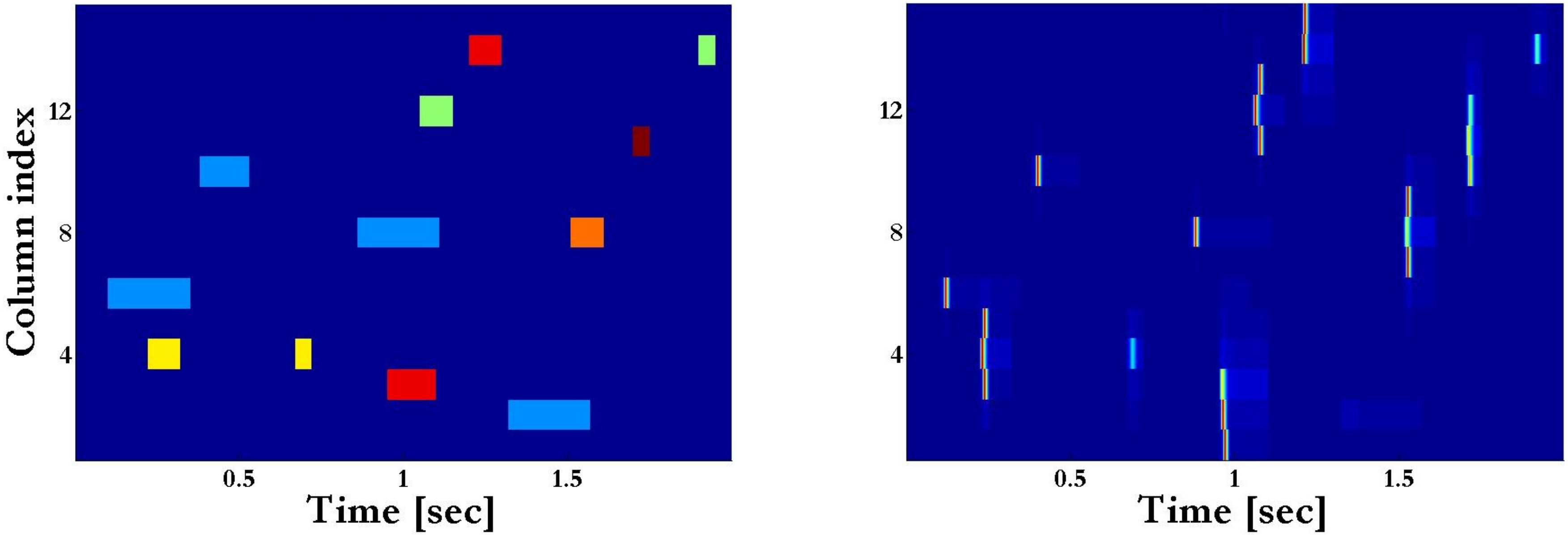
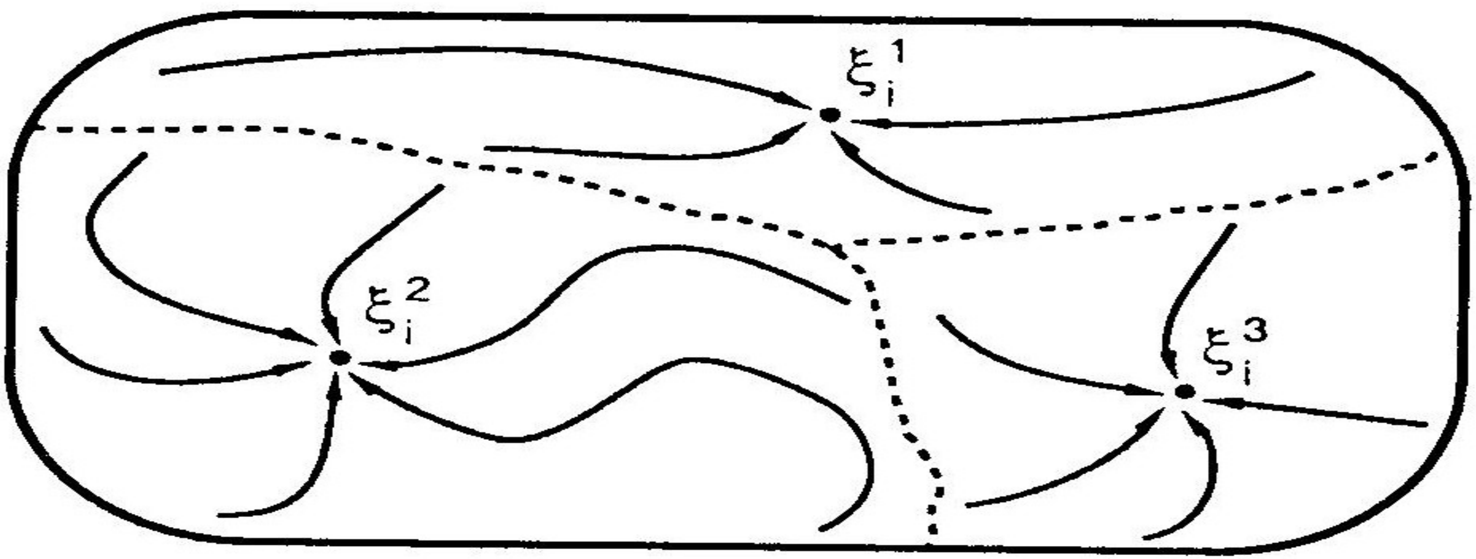
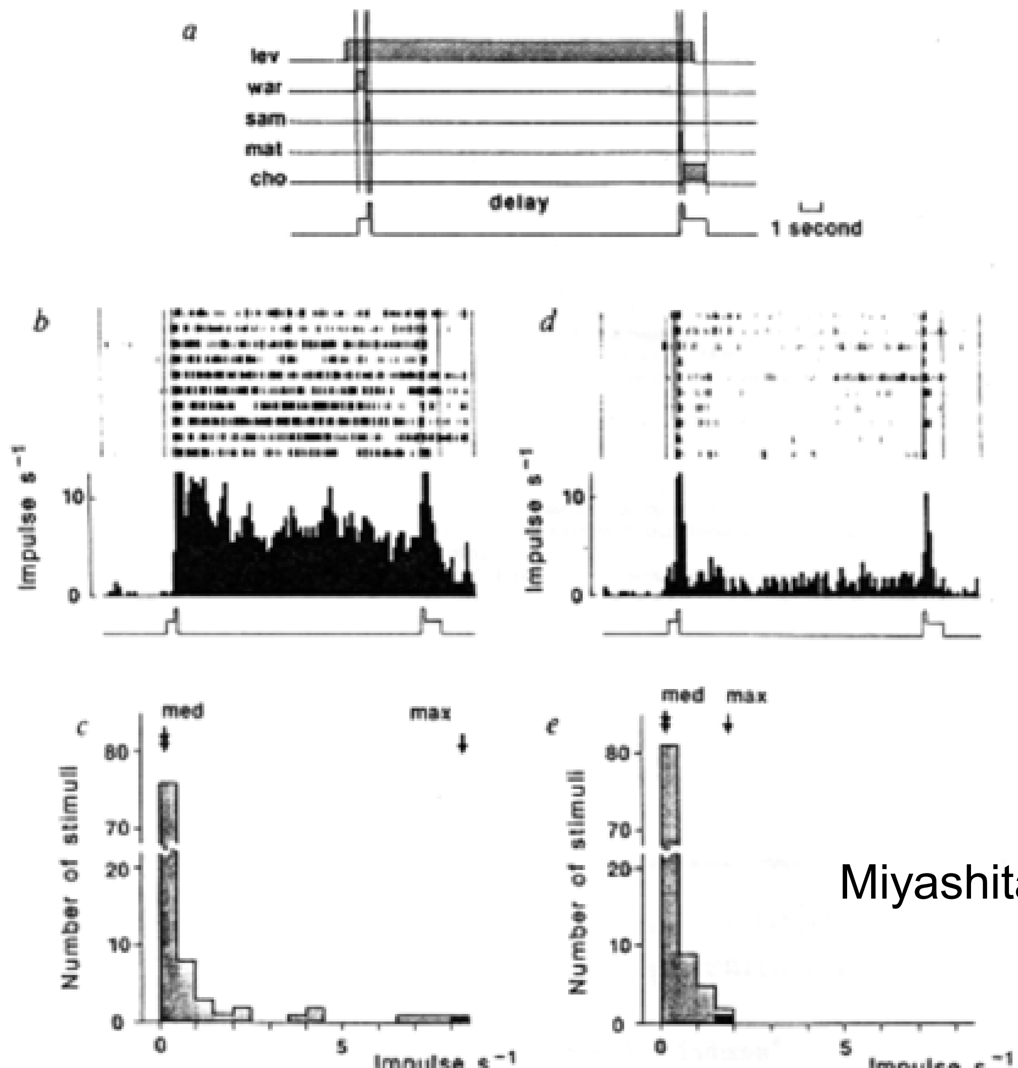


Synaptic theory of working memory

Memory patterns as network attractors

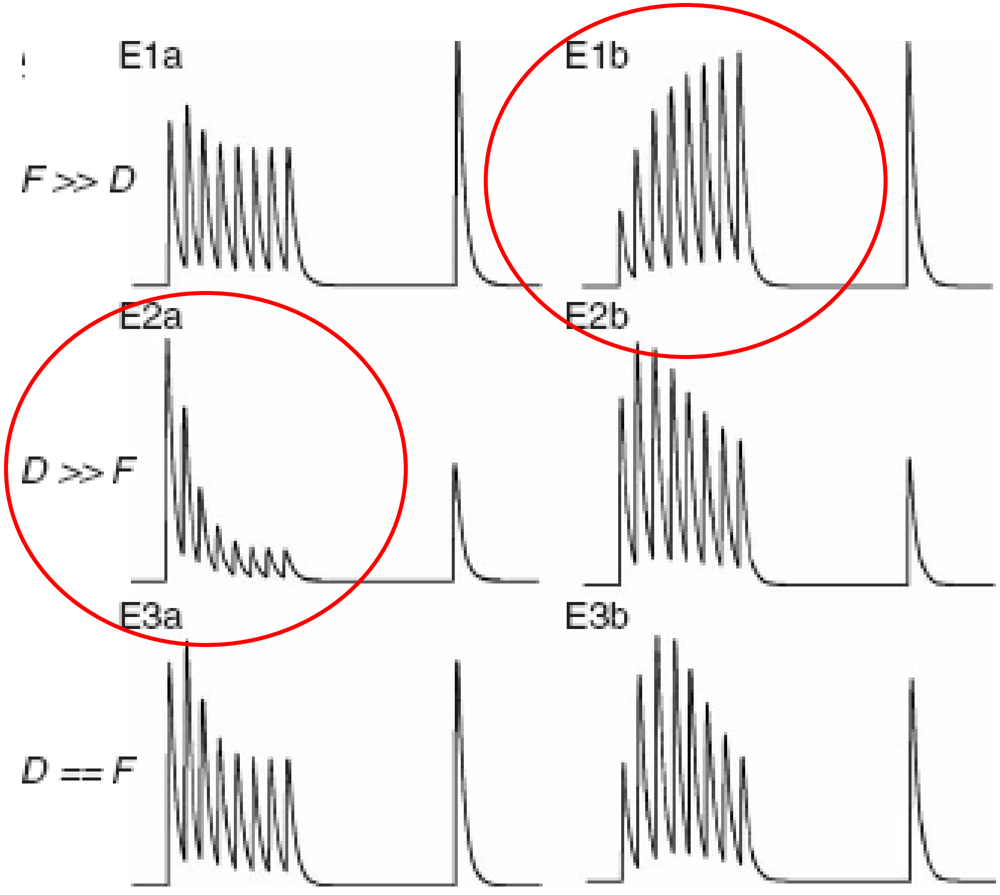


Persistent activity



Miyashita et al, Nature 1988

Synaptic diversity in the pre-frontal cortex



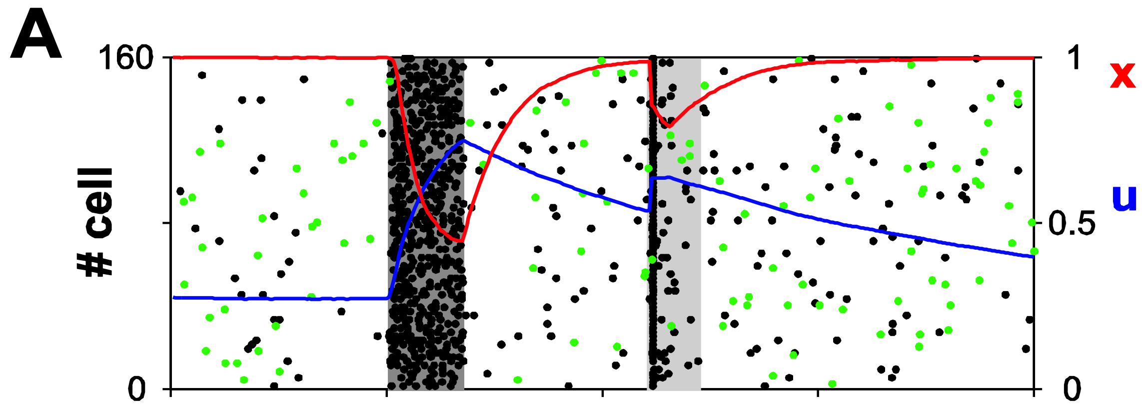
Wang, Markram et al, Nature Neuroscience 2006

New idea

- To hold short-term memories with facilitation level of recurrent connections
- Use spiking activity only when the memory is needed for processing, and/or to refresh the synapses (‘rehearsal’).

Mongillo, Barak & Tsodyks 2008

Integrate and fire network simulations



Thanks to:

Henry Markram (WIS)

Asher Uziel (WIS), Alex Loebel (WIS) & Eli Nelken (HUJI)

Gianluigi Mongillo (ENS) & Omri Barak (WIS)