Information Processing in Cortical Neural Networks with Dynamic Synaptic Connections

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Complexity in Jerusalem 2008
Feed-forward networks: Perceptron

\[ O = \text{sign} \left( \sum_i J_i x_i - T \right) \]
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

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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
Testing the Model: Depressing Synapses

\[ U \leq 0.5 \quad \tau_d \leq 1 \text{sec} \quad \tau_f \rightarrow 0 \]
Facilitation \( (\tau_f >> \tau_d) \)
Facilitation ( $\tau_f \gg \tau_d$)

$U \equiv 0.1 \quad \tau_d \equiv 0.1\text{sec} \quad \tau_f \equiv 1\text{sec}$
The 1/f Law of Release

Synaptic depression and neural signalling
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Spiking activity $\rightarrow$ Synaptic current
Emergence Of A Transient Signal

**Simulation**
- 1 Hz
- 10 Hz
- 40 Hz

**Experiment**
- 1 Hz
- 10 Hz
- 40 Hz

- 500 neurons
- Average 200 sweeps

- 1 nA
- 0.5 s
- 1 mV
- 0.5 s
Recurrent networks with synaptic depression
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: \( I_s(t) = \sum_{sp} i_s(t - tsp) \)
Simulation of Network Activity

![Graph showing network activity with weak coupling](image)
Simulation of Network Activity

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, $x$:

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

Loebel & Tsodyks 2002
Bifurcation

\[ J < J_{cr} \]
\[ J > J_{cr} \]
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

Broad-band noise

Sub-threshold Tone

Time [\(\tau_{rec}\)]
Hyper-sensitive locking suppression

(Nelken et al, Nature 1999)
Network response to complex stimuli
Network response to complex stimuli
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
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