BNN Course: Synaptic Plasticity

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Synaptic plasticity

- considered to be the biological substrate of learning and memory

Synaptic changes can be induced by specific stimulation conditions for example defined through

- presynaptic firing rates
- spike timing

Detailed biophysical models

- crucial to understand undelying biological mechanisms

Phenomenological models

- describe synaptic changes without reference to mechanism
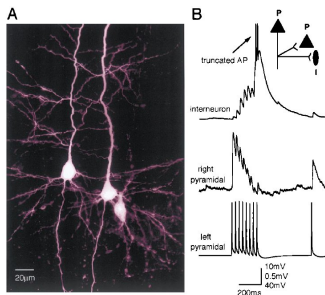- generally more tractable and less computationally expensive

Outline

Basic experimental findings

Short-term plasticity

Long-term plasticity

Spike-timing dependent plasticity

Homeostasis

Phenomenological models of synaptic plasticity

Short-term plasticity (very briefly)

Spike-timing dependent plasticity (in detail)

Short-term plasticity

Markram et al. (1998)
Proc Natl Acad Sci USA. **95**(9):5323–5328

- ► sequence of eight presynaptic spikes at 20Hz evokes successively smaller (depression) or successively larger (facilitation) responses in postsynaptic cell
- ► same presynaptic neuron makes connections to different types of target neurons with different plasticity properties

- ► depends on sequence of presynaptic spikes on a time scale of tens of milliseconds
- ► change persists only for a few hundred milliseconds (amplitude of the postsynaptic response recovers to close-to-normal values within less than a second)

Long-term plasticity
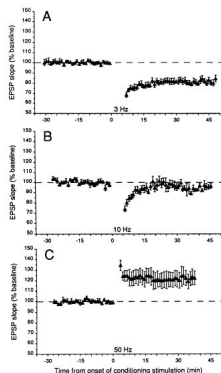
- 900 presynaptic stimulation pulses yield either persistent depression (LTD) or potentiation (LTP) depending on rate

  Dudek & Bear (1992)
  Proc Natl Acad Sci USA. **89**:4363–4367

- sensitive to the presynaptic firing rate over a time scale of tens or hundreds of seconds

- change can persist for more than one hour

- final stabilization on a time scale of hours
  (e.g. late phase of LTP reported by Frey & Morris, 1997)
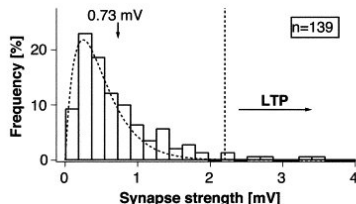
Long-term plasticity
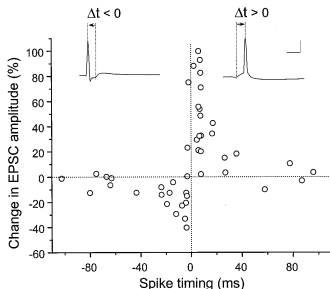
- ▶ LTP if presynaptic spike precedes postsynaptic spike by 10 ms
- ▶ LTD if order of spikes reversed
- ▶ repetitions of 60 pairs of spikes (single pair has no effect)

- ▶ depends on exact timing of pre- and postsynaptic spikes on time scale of milliseconds
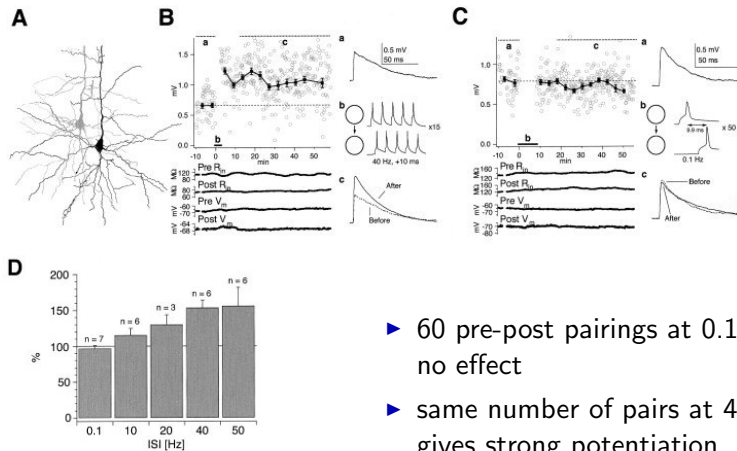- ▶ so called spike-timing dependent plasticity (STDP)

Spike-timing dependent plasticity (STDP)

Sjostrom et al. (2001) *Neuron.* **32**(6):1149–64

- ▶ synaptic strength (e.g. EPSP amplitudes) in data collected across several pairs of neurons reported to be unimodal
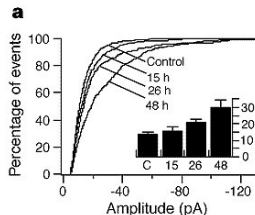
Spike-timing dependent plasticity (STDP)

▶ 60 pre-post pairings at 0.1 Hz have no effect

▶ same number of pairs at 40 Hz gives strong potentiation

Sjostrom et al. (2001)
Neuron. **32**(6):1149–64

▶ depends on repetition frequency of pre-post spike-pairings

Homeostasis of synaptic efficacies

Turrigiano et al. (1998)
Nature. **391**:892–896

- chronic blockade of cortical culture activity increases amplitude of mEPSCs

- on a time scale of hours, rescaling of synaptic response amplitudes may occur
- useful to stabilize neuronal firing rates

Phenomenological models of short-term plasticity
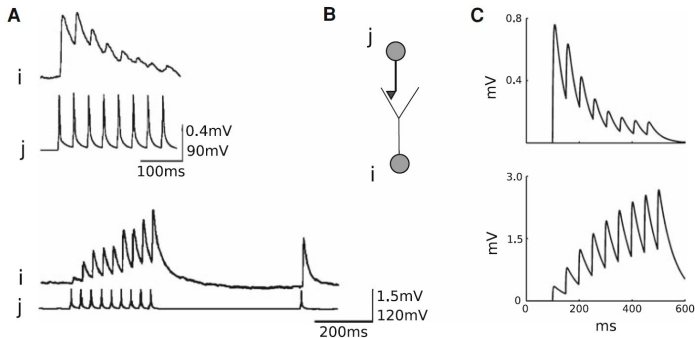
Left: experimental results adapted from Markram et al. (1998)

Right: simulation results using Markram-Tsodyks model

- ▶ fast synaptic dynamics firmly established in biological literature (Markram et al. 1998; Gupta et al. 2000)
- ▶ well-accepted models exist (Abbott et al. 1997; Tsodyks et al. 1998)

Phenomenological models of spike-timing dependent plasticity

What do we need to specify a pair-based model of STDP?
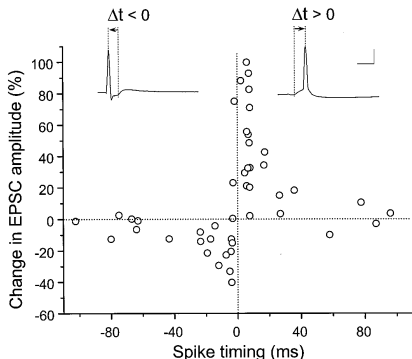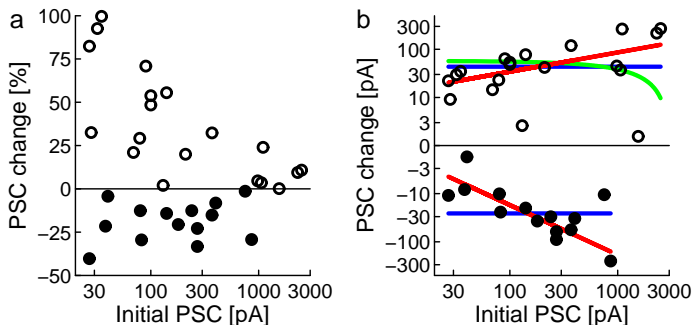

$$\Delta w_- = -F_- (w) \exp \left(- |\Delta t| / \tau_- \right)$$
$$\Delta w_+ = -F_+ (w) \exp \left(- |\Delta t| / \tau_+ \right)$$

- ► weight dependence
  i.e. $F_{\pm} (w)$

- ► spike pairing scheme

- ► decomposition of synaptic delay into axonal and dendritic components

all of these aspects are important
and should not be chosen arbitrarily

Models of STDP: Weight Dependence

- Reanalysis of Bi & Poo (1998) data shows that the commonly used additive model ($F_- = A_-$, $F_+ = A_+$) is not a good fit for the data.

- Depression data are best fit by a multiplicative/power law model ($F_- = A_- w^{-1}$)

- Potentiation data are best fit by a power law model ($F_+ = A_+ w^\mu$, $\mu = 0.4$)
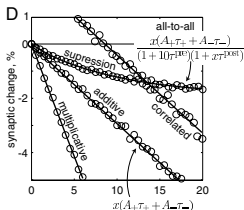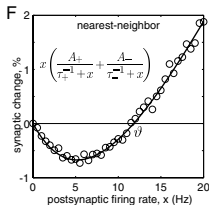
Models of STDP:
Distribution of synaptic weights
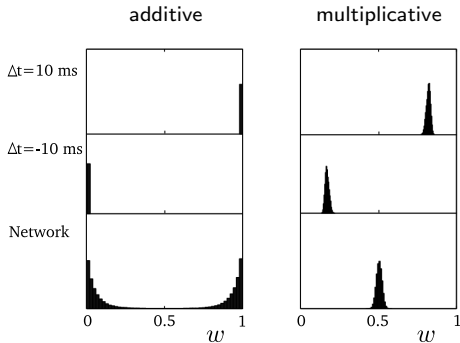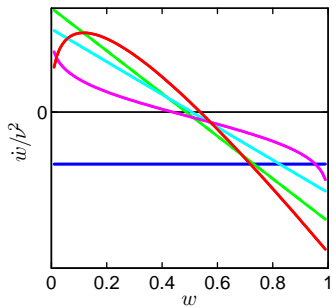
- all weight dependent models exhibit a stable fixed point and generate a unimodal distribution (multiplicative, power law, Gütig, Van Rossum)

- the additive model does not have a stable fixed point and produces a bimodal distribution
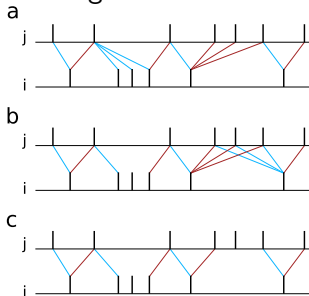
Models of STDP: Spike Pairing Scheme

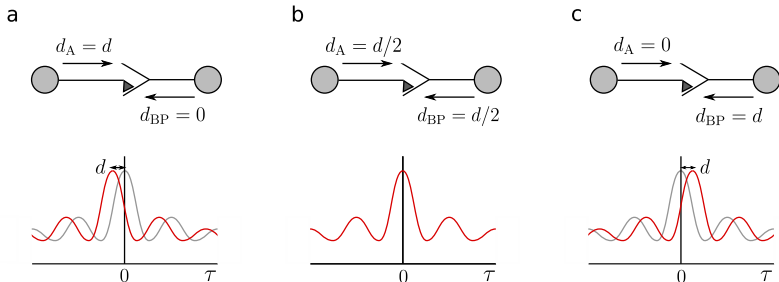all-to-all...   ... or nearest neighbour?   ...but which nearest neighbour?

Izhikevich & Desai (2003) *Neural Comput* **15**:1511–1523

- there are many possible spike pairing schemes
- they can give qualitatively different results (e.g. Kempter et al. 2001; Morrison et al. 2007)
- see Burkitt et al (2004) for copious analysis

Models of STDP: Synaptic Delays

- The synaptic drift depends on the cross-correlation with respect to the synapse
- This is shifted from to the left or right of the (measurable) cross-correlation with respect to the soma depending on whether the synaptic delay is largely axonal (a) or dendritic (c)
- Therefore the same STDP rule coupled with the same network dynamics can give rise to either net depression, no change, or net potentiation
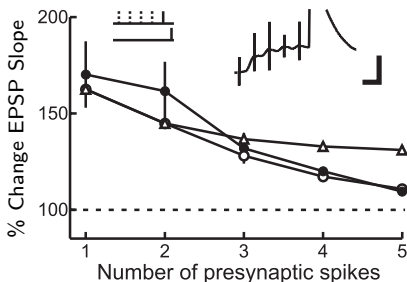
Models of STDP: Beyond Pair Effects

Many features of STDP cannot be explained by pair-based rules:

Frequency dependence
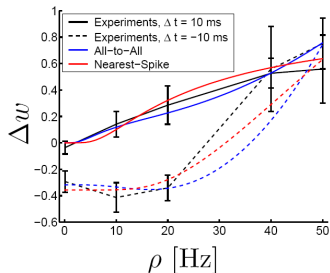
Data: Sjostrom et al. (2001) *Neuron* **32**:1149–1164
Modelling: Pfister et al. (2006) *J Neurosci* **26**:9673–9682

Burst dependence

Data and modelling: Froemke et al. (2006) *J Neurophysiol* **95**:1620–1629

There is generally no cross-compatibility between models accounting for these features

Conclusions

- A modeller needs to specify a complete model despite lack of clear experimental evidence
- These choices can have profound consequences
- Almost all network modelling papers fail to consider whether the effects shown are artifacts of their specific choices
- There is so far no phenomenological model which accounts for all the nonlinearites exhibited by STDP
- For those who want to know more...

Phenomenological models of synaptic plasticity based on spike timing

**Abigail Morrison · Markus Diesmann ·
Wulfram Gerstner**