Learning and Memory - Synaptic Plasticity

Informatics 1 Cognitive Science

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Topics

- Different forms of learning
- Hebbian Synaptic Plasticity
- Neural assemblies
- Hebbian Assemblies
- Summary

Learning

An adaptive change in the brain for acquisition/updating of knowledge and behaviours:

Non-associative learning Changes due to exposure to a stimulus, includes "learning from data", adaptation/habituation (traffic noise) and sensitisation (pain increases sensitivity to other stimuli).

Associative learning Learning about the association of two stimuli or events, such as operant (reinforcing stimuli, e.g. hot surface, "voluntary") and classical conditioning (unrelated stimuli, e.g. tone and food, "involuntary").

Supervised and Unsupervised Learning

Supervised learning:

- Assumes a teaching signal exists: Memory representations are modified according to an error or objective function (e.g. data labels, a desired task outcome and so on).
- Example: The perceptron rule or the backprop algorithm with error function.
- Powerful but requires careful specification of the objective, and brain circuits dedicated to computing it.

Supervised and Unsupervised Learning

Unsupervised learning:

- A learning rule that builds useful representations from data ("structure from data", e.g. from sensory inputs).
- Examples: Principal Component Analysis, clustering and density estimation more generally.
- Recent ML methods: self-supervised learning and generative models.
- Thought to underlie development of early sensory representations in the cortex.

It is currently unclear how much the brain can/does learn in a purely unsupervised manner.

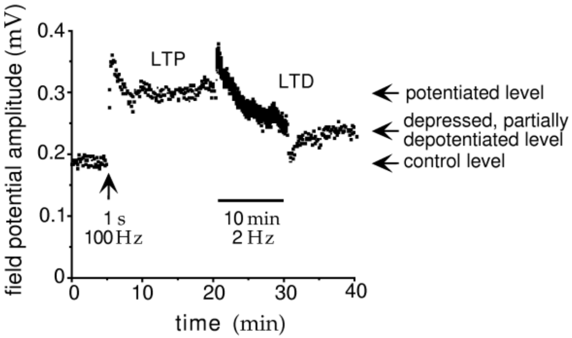
The basis of learning: Hebbian Plasticity

In 1949 Donald Hebb, who was thinking about reverberating loops in networks of neurons, postulated that:

“When an axon of cell A is near enough to excite cell B or repeatedly or consistently takes part in firing it, some growth or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.”

“Cells that fire together wire together”

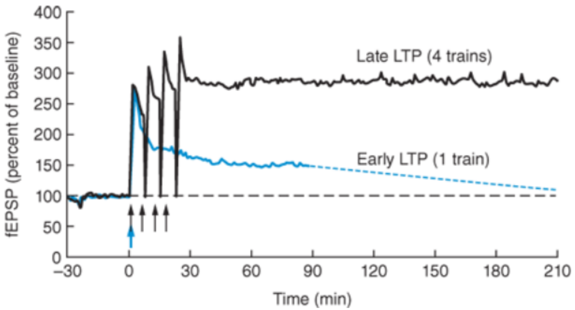
Synaptic Plasticity, the Basis of Memory



Depending on the input and activity of a neuron, a synapse can either show *long term potentiation* (LTP) or *long term depression* (LTD). These changes can persist for a long time (at least for months).

Discovered by: Bliss, T.V.P. and Lomo, T., J. Physiol. 232 (1973), pp. 331–56.

Early and Late LTP



A weak stimulus causes short-lasting LTP, while a strong stimulus causes permanent LTP (depends on protein synthesis).

A simple mathematical model of Hebbian Plasticity

Idea: "Neurons that fire together, wire together."
Activity of a neuron (e.g. firing rate):

$$y = f\left(\sum_{j=1}^{N} w_j x_j\right) = f(\mathbf{w}.\mathbf{x})$$

where **w** are the weights of the synaptic inputs and **x** the activities of other neurons.
Weight changes are then

$$\begin{aligned}\Delta w_i &= \epsilon y x_i \\ &= \epsilon x_i \sum_{j=1}^{N} w_j . x_j\end{aligned}$$

where ϵ is a small constant learning rate.

Is this model sufficient to explain learning?

Here the weights simply track the correlations between inuts and output activity:

$$\Delta w_i = \epsilon y x_i$$

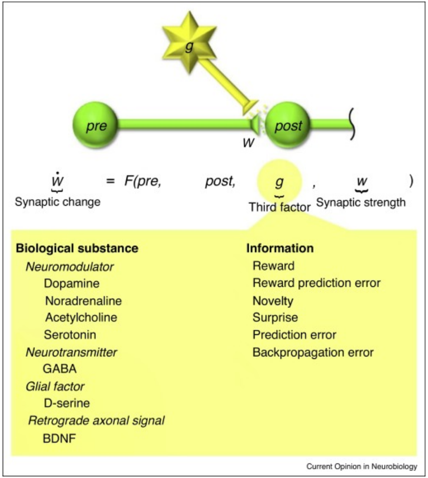
Problems:

- Learning is unstable: Potentitation causes more potentiation, activity goes to infinite.
- The learning rate ϵ determines the speed of learning. If large (e.g. one-shot learning), learning is fast, but even more unstable.

Solutions:

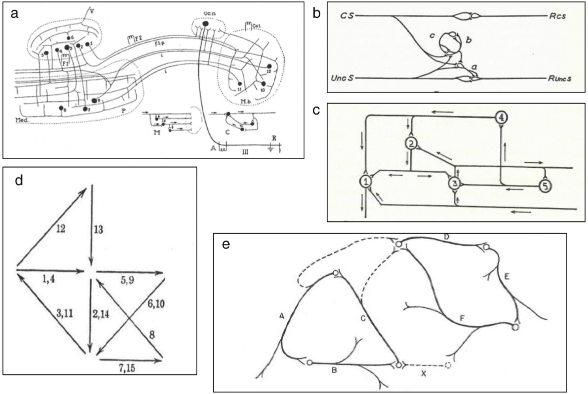
- A bounded w_{ij}.
- A rule based on covariance: $(y - < y >)(x_i - < x_i >)$.

Supervised learning: three-factor learing



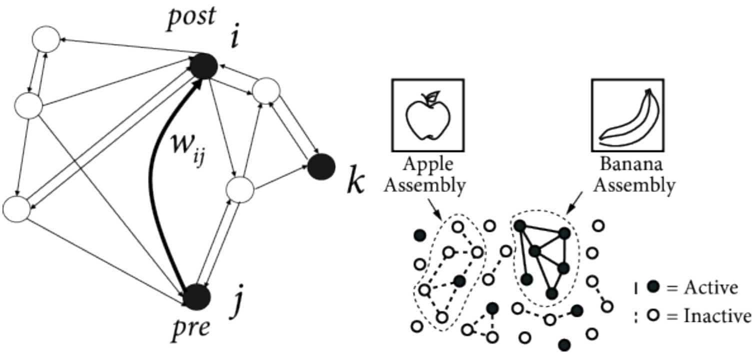
A thord factor in a learning rule can act as superviory signal.

Hebbian Assemblies



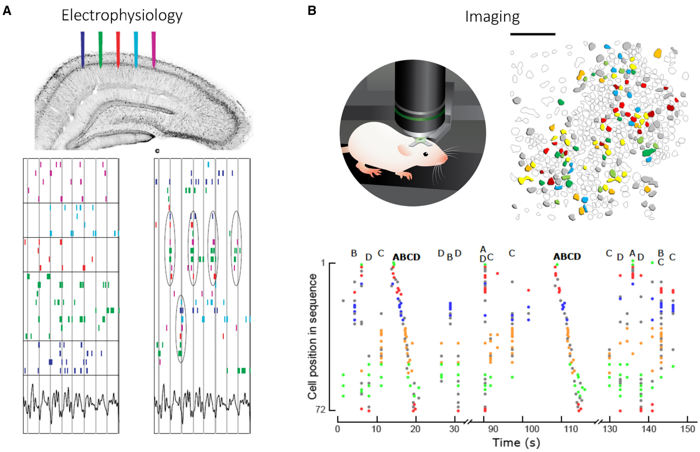
Hebb suggested reverberatory activity underlies learning and memory (1949): (a) Oculo-motor circuits, (b) simple conditioning circuit model, (d) a reverberating circuit, (d) schematics of a reverberating circuit (a Hebbian assembly) (e) two assemblies A-B-C and D-E-F (in an association cortex), where synapse strengthening leads to reverberation in the circuit.

Hebbian Assemblies



Assemblies can arise from stimulation of a subset of input neurons, where plasticity leads to a stable representation of the input by recruiting additional neurons.

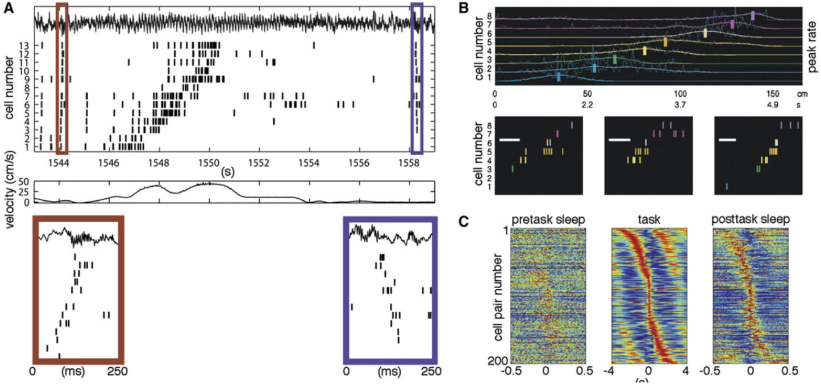
Hebbian Assemblies in Hippocampus



Hippocampal activity during spatial exploration (colours code for recording locations), assemblies become visible by re-arrainging the activity patterns.

Yuste, R., Cossart, R., & Yaksi, E. (2024). Neuronal ensembles: Building blocks of neural circuits. Neuron.

Hebbian Assemblies in Hippocampus



Sequences of place cells during navigation are replayed during rest (A) or sleep (B).

Buzsáki, G. (2010). Neural syntax: cell assemblies, synapsembles, and readers. Neuron, 68(3), 362-385.

Summary

- Learning can be supervised or unsupervised.
- Synaptic plasticity is the neural basis of memory and learning.
- Hebbian plasticity is a simple rule that can explain the formation of neural assemblies.
- Supervised learning can be implemented by a three-factor rule.
- Assemblies can be formed by Hebbian plasticity.
- There is ample evidence for the existence of neural assemblies.