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Collective information storage in multiple synapses enables fast learning and slow forgetting

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Most of the excitatory cortical synapses reside on dendritic spines. Although these spines undergo a remarkably high turnover [1,2], they have been shown to be involved in learning and long-term memory. Along this line, it is unclear how information is preserved while its substrate (synapses or spines) is permanently changing.

Here, we use a simple stochastic model of structural plasticity to investigate this phenomenon: We assume a certain number of potential synaptic locations from one neuron to another.

At those locations, synapses (spines) are created with a constant probability and removed with a probability depending on the number of existing synapses and the stimulation of the neurons. From these two probabilities, the stationary distribution of the number of synapses between two neurons can be calculated.

Experimental measurements of these stationary probability distributions in the cortex show that the majority of connections has either zero or multiple synapses while one or two contacts are very improbable [e.g., [3-5]]. Using information theoretic measures we show that, in our model, such bimodal distributions enable information storage over time scales many orders of magnitudes higher than the involved probabilities. Thus, in this system the conflict of rapid spine turnover (probabilities) and long-term memory is resolved by storing the information collaboratively in multiple synapses.

In the following, we will consider the bimodal stationary distributions as the working point of the system. Then, we can model external signals, as, e.g., increased or decreased activities during learning, as changes of the removal probabilities and stationary distributions (e.g., mediated by synaptic plasticity [6]).

For instance, for learning signals resulting to unimodal stationary distributions (only connected or only unconnected), we find that learning is orders of magnitude faster than forgetting. Along this line, we observe that retraining a task does not induce an increased overturn rate as during initial training, which has been similarly observed for dendritic spines in vivo [1,2]. Our results clearly relate the difference in time scales to the shape of the stationary distribution and therefore reveal the functional advantage of the bimodal distribution found in experiment.

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