Distinct dopaminergic spike-timing-dependent plasticity rules are suited to different functional roles | Jonathan Rubin

Authors: Baram Sosis & Jonathan E. Rubin, University of Pittsburgh, Department of Mathematics

Abstract: Inspired by experimental findings, various mathematical models have been formulated to describe the changes in synaptic strengths resulting from spike-timing-dependent plasticity (STDP). One site where STDP is believed to play a key role is at cortico-striatal synapses, which comprise the primary channel for cortical inputs to the basal ganglia. The neuromodulator dopamine is released by midbrain dopamine neurons when unexpected reward is received and interacts with the timing of pre- and postsynaptic spiking to modulate plasticity of cortico-striatal synapses. Experimental and theoretical analysis of cortico-basal ganglia-thalamic (CBGT) circuits suggest a key role for dopaminergic reward prediction error signals, through their impact on cortico-striatal synaptic strengths, both in updating value estimates associated with available choices and in altering the likelihood that a particular action will be selected in the future [1]. These distinct functions are likely performed by different neurons in different regions of the basal ganglia, however, which raises the possibility that distinct plasticity rules are involved. Unfortunately, despite some exciting experimental investigations of long-term plasticity properties in specific striatal regions and task settings, relatively little is known about the details of these plasticity mechanisms, especially in striatal regions thought to encode value. We sought to address this gap by analyzing, mathematically and with simulations, the performance of a set of three potential dopamine-dependent STDP models across several biologically relevant scenarios.

Two of the plasticity models considered comprise previously proposed STDP rules [2] with modifications to incorporate dopamine, while the third is a dopamine-dependent STDP rule tailored specifically to cortico-striatal synapses, based on experimental observations [3]. We tested the ability of each of the three models to complete simple reward prediction and action selection tasks and to maintain its weights in the face of noise, studying the learned weight distributions and corresponding task performance in each setting (see Figure 1

of the supplementary material). Mathematically, each model is a coupled system of ordinary differential equations for synaptic weights posed at the individual synapse level, driven by a Poisson cortical input, together with additional terms to implement postsynaptic firing and dopamine release and to track each synapse's time-dependent eligibility for plasticity. Our analysis proceeds via the derivation and analysis of average weight drift equations for each model. Although technical, this step leads to equations for which we can assess the existence of critical points and, in some cases, prove that certain conditions are necessary and/or sufficient for their stability (see Figure 2 of the supplement). For example, in the reward prediction setting, for two of the models, the evolution equation for the average weight w_i is

$$dw_i/dt = (R^* - N\langle w,r\rangle)*r*(tdop)*(teli)*[\tau*\Delta f(w_i)*r_i*\langle w,r\rangle+(f+)(w_i)*w_i*r_i]$$

where various constants are model parameters including a target firing rate R*, an input rate vector r, and various time constants, and where the f terms relate to plasticity effects of different relative spike timings, which depend on the specific model being considered. Interestingly, we find that each of the three plasticity rules is well suited to a subset of the scenarios studied but falls short in others. We show that this result generalizes to more complex variants of these settings in which the reward contingencies or the task changes periodically. These results show that different tasks may therefore require different forms of synaptic plasticity, yielding the prediction that the precise form of the STDP mechanism present may vary across regions of the striatum, and other brain areas impacted by dopamine, that are involved in distinct computational functions.

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