Modeling the Mechanisms of Reward Learning that Bias Visual Attention

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A body of recent research has shown that visual attention is biased toward rewarded stimuli. Because of the known role of the basal ganglia in reward learning, a potential mechanism for this bias is learning in striatal medium spiny neurons (MSNs, see Fig. 1), which receive projections from cortex carrying information about visual stimuli and from dopaminergic neurons carrying information about reward. Furthermore, their output can influence visual processing through the closed visual corticostriatal loop, that runs from the MSNs through globus pallidus/substantia nigra (GPi/SNr), thalamus, and back to visual cortex. We propose an implementation for this closed visual loop (Fig. 1) that includes a biologically plausible model for temporal cortical neurons and striatal MSNs, both simulated through the Adaptive Exponential Leaky Integrate and Fire (AdEx LIF; Eqs. 1 and 2) model:

$$\tau_m \frac{dv}{dt} = -(v - v_{rest}) + \Delta T \times e^{\frac{v - \vartheta_{rh}}{\Delta T}} + R(I - u - I_{AMPA} - I_{GABA}) \quad (1)$$

$$\tau_u \frac{du}{dt} = a\,(v - v_{rest}) - u \quad (2)$$

with parameters constrained with data from the neurophysiological literature. Exponential LIF models (Eq. 1) were used for the GPi neurons as well as the thalamic neurons. The strength of synapses (w) between visual and striatal neurons are modified in each learning trial through a biologically-plausible reward-driven learning rule:

$$w_{new} = w + \eta \Omega(\mu_{Ca}) DA(1 - w) \quad (3)$$

where $\Omega\,(\mu Ca)$ is a nonlinear function of the mean calcium concentration inside the cell and DA represents dopamine concentration outside the cell. Through association, the model initially adjusts these synapses based on the paired presentations of a particular color and a high reward or a lower reward. Adjustments were made until the reward prediction error was small. Using these acquired cortical-striatal weights while following the setup of a typical experiment in reward-based attentional bias, the model then selected a target shape from among five distractor shapes. One distractor had a previously-rewarded color. The model took significantly longer to make decisions when the distractor associated with a higher reward was present compared to when the distractor associated with lower reward was present (Fig. 2). Thus, the model can explain reward-based attentional capture through neurobiologically-plausible learning mechanisms. Furthermore, the model is in line with results from the neurophysiological and neuroimaging literatures that implicate the visual corticostriatal loop in reward-based visual learning.

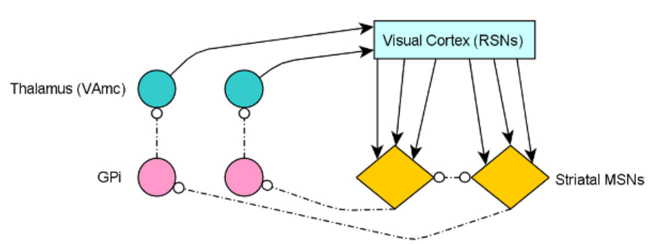

Figure 1: This model is of the closed corticostriatal loop as depicted above. In this figure, dashed lines are inhibitory connections and solid lines are excitatory.

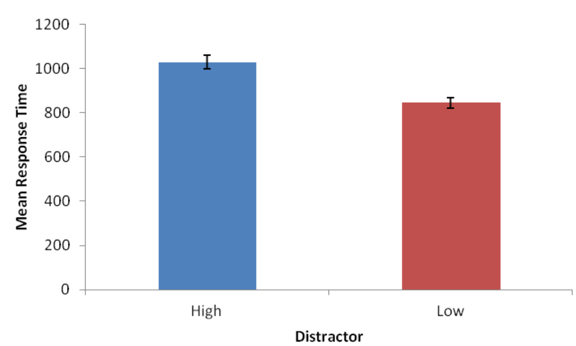

Figure 2: When the more rewarding distractor is present, the response time is longer than when the less rewarding distractor is present.