Basal Ganglia Contributions to Logical Operations in Humans

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Abstract:

The basal ganglia are thought to selectively gate cortical information flow, thereby enabling action selection (Chevalier & Deniau, 1990), working memory updating (Frank et al., 2001), and decision-making (Lo & Wang, 2006; Ding & Gold, 2012). Here, we provide human fMRI evidence that sequential, deductive reasoning recruits the basal ganglia, and does so in a manner consistent with a system-level implementation of simple logic (AND/OR) gates. Specifically, regions of the midbrain and caudate nucleus show an early increase in BOLD signal for OR (low-threshold) trials, relative to AND (high-threshold) trials, consistent with a bias signal for OR. During reasoning, for AND trials only, increases in caudate activity are offset by a decrease in putative indirect pathway activity (GPe). This GPe decrease may prevent premature inference for AND by transiently reducing its tonic inhibition on the BG output nuclei. Finally, when the subject makes an inference, there is a decrease in the activity of a distinct bilateral midbrain/globus pallidus region. This decrease may release thalamic-cortical pathways from prior inhibition, thereby reflecting logical gating. Though preliminary, these results are broadly consistent with computational models of perceptual decision-making in BG (Wei et al., 2015), extended to a verbal logical reasoning task over discrete, sequential inputs.

Keywords: logic; basal ganglia; fMRI; reasoning; decision-making

McCulloch and Pitts (1943) (MP) famously developed artificial neuron models that could compute simple logical functions, such as the AND and OR operators. MP neurons compute these functions by (1) passing their input through a non-linearity to produce a discrete output, reflecting a truth value, and (2) varying the neuron's response threshold: a high threshold can be used to implement AND, and a low threshold for OR operator. Though work on the neural circuits underlying propositional reasoning in humans has focused on a fronto-parietal network (Prado et al., 2011), the basal ganglia are computationally well-suited to work in concert with these regions to support logical reasoning. Specifically, the basal ganglia have been hypothesized to gate cortico-cortical communication by transiently dis-inhibiting specific thalamic-cortico pathways (Chevalier & Deniau, 1990; Frank et al., 2001; Lo & Wang, 2006). Here, we explore the possibility that the basal ganglia contribute to Boolean operations by selectively modulating an inference-threshold (low OR, high AND), and implementing a non-linear gating operation to signal logical inference, analogous to system-level MP logic gates.

Method, Analysis, & Results

24 participants performed a two-alternative (yes/no), fixed-duration deductive reasoning task**,** while undergoing functional magnetic resonance imaging (fMRI)**.** Trials had the following form: *Lucy can watch TV-- if and only if--she washes the dishes --and--walks the dog.--She has now washed the dishes--She has not walked the dog--Can Lucy watch TV?* Information was presented sequentially, and the '--' symbols above indicate new presentation screens, separated by jitters.

We first contrasted univariate BOLD signal for OR and AND trials during the period in which information about the relevant logical operator had been presented, but information about the truth or falsity of the premises had not (see Figure 2). During this time period, we find that the right midbrain and right caudate nucleus respond more to OR than AND trials ($p<0.005$ voxelwise, $p<0.05$ small volume corrected). These results are consistent with an early bias signal, effectively lowering the inference threshold for OR. Though it is hard to precisely localize the source of this midbrain effect with fMRI, one interesting possibility is that this signal originates in the substantia nigra pars compacta (SNc) The SNc provides dopaminergic input to the striatum (see Figure 1), which may reduce the threshold, controlled by the caudate. We are currently working to identify the anatomical source of this effect more precisely.

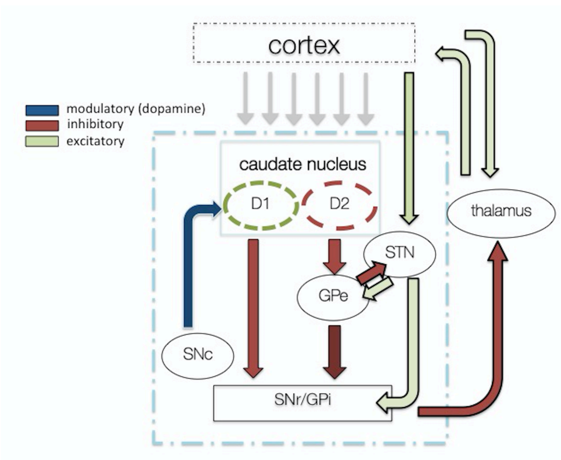

Figure 1: Schematic of classic model of basal ganglia connectivity.

During the reasoning period, we see a decrease in activity in a bi-lateral midbrain/Globus Pallidus interna (GPi) ROI on screens in which an inference is licensed, relative to those in which it is not (Figure 2. Panel 3). The SNr/GPi are thought to act as a gate by tonically inhibiting the thalamus (e.g., Frank et al., 2001) (see Figure 1). Less activity during inference suggests that this tonic inhibition is lifted, and the gate has been opened to signal inference.

On "no-inference" premises (i.e., AND, yes; OR, no), we find an increase in caudate nucleus (CN) activity for AND relative to OR ($p<0.005$, $p<0.05$ clusterwise), and a corresponding decrease in GPe activity. The GPe tonically inhibits the SNr/GPi (see Figure 1). The net effect of GPe reduction is thus to prevent pre-mature inference (SNr/GPi decrease) upon increases in CN activity (Wei et al., 2015). These data thus suggest multiple possible mechanisms for threshold control in the BG: one in which a threshold is lowered for OR by an increase in midbrain/CN activity prior to reasoning, and a second in which GPe activity is selectively reduced during reasoning to implement a higher-threshold (AND) by requiring more CN activity to drive a SNr/GPi decrease, and hence logical inference.

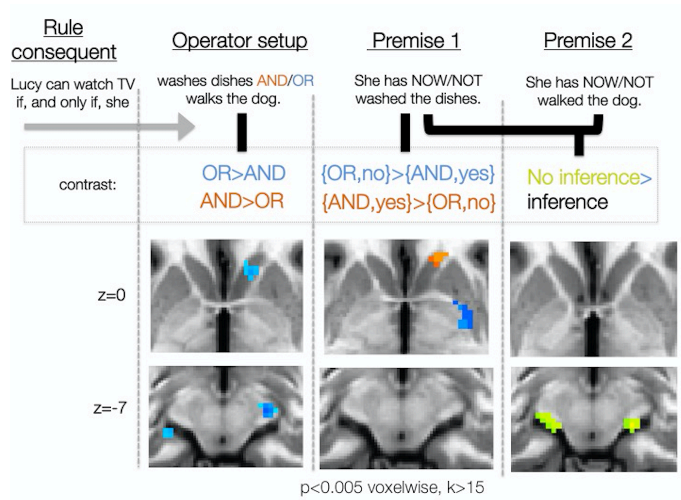

Figure 2. Sub-regions of BG showing operator and inference effects.

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