A Computational Model of the Role of Cortico-basal-thalamic Loops in Planning and Executive Control

Srini Narayanan
ICSI and University of California, Berkeley
snarayan@icsi.berkeley.edu

1 Abstract

Clinical and experimental research over the last decade has implicated neuroanatomic loops connecting the frontal cortex to the basal ganglia and thalamus in various aspects of planning and memory. We report on a computational model whose central aspects are (1) a model of cortical-striatal-thalamic loops in planning and executive control, and (2) a fine-grained model of basal-ganglia function that exploits specific component connectivity and dynamics. The model is biologically plausible given current literature on the neurophysiology and disease pathology of the relevant brain regions. Specifically, our model has implications for subjects with diseases affecting the relevant brain regions (Parkinson's disease (PD) and Huntington's disease (HD)).

2 Summary of Paper

Clinical and experimental research over the last decade has implicated neuroanatomic loops connecting the frontal cortex to the basal ganglia and thalamus in various aspects of planning and memory. This paper reports on a computational model whose central aspects are (1) a model of cortical-striatal-thalamic loops in planning and executive control, and (2) a fine-grained model of basal-ganglia function that exploits specific component connectivity and dynamics. The model is biologically plausible given current literature on the neurophysiology and disease pathology of the relevant brain regions. Specifically, our model has implications for subjects with diseases affecting the relevant brain regions (Parkinson's disease (PD) and Huntington's disease (HD)).

There is by now robust evidence that the pre-frontal cortex plays a key role in various aspects of working memory and executive control. As [Middleton & Strick 2000] point out, there is also clear evidence that the basal ganglia are closely involved with prefrontal cortex activity. Specifically, damage to the basal ganglia produces cognitive deficits comparable to prefrontal cortex malfunction. Recently, researchers have attempted to identify the individual roles played by the basal ganglia and the prefrontal cortex through computational modeling and simulation [Amos 2000, Frank, et al., 2000, Taylor & Taylor, 2000].

Many recent models have identified the role of the basal ganglia as one of *selective disinhibition*. These models assume that cortical afferents are integrated by the striatum (the main input nuclei of the basal ganglia). Cells from the striatum project topographically through inhibitory connections to the pallidal and negral output nuclei of the basal ganglia. When a striatal match is found (where all the appropriate input cortical areas are active), The tonic activity of the appropriate output cells is suppressed through increased inhibition. This suppression in turn disinhibits the thalamus and through it the appropriate prefrontal region (through segregated and topographic projections). Thus, the main role of the basal-ganglia in these models is one of integrating inputs from multiple cortical areas through conjunctive cortico-striatal connections and then selectively disinhibiting particular areas in the prefrontal cortex based on the result of the match.

Our model of the basal ganglia differs from previous models in that it incorporates the specific connectivity and dynamics of the various basal ganglia modules. Specifically, the model incorporates multiple pathways within the basal ganglia including a) the *direct pathway* (striatum - substantia negra pars reticula (SNR) - globus pallidus interna (GPI)), b) the *indirect pathway* (striatum- globus pallidus externa (GPE) and SNR/GPI), c) the *internal loop* between GPE and the subthalamic nucleus (STN), and d) *direct excitation* of the STN. In the model, SNR/GPI nuclei are tonically active and inhibit the thalamus. The projections from the SNR/GPI to the thalamus are topographically organized. When active, the direct pathway results in inhibiting the basal ganglia output nuclei and thus disinhibiting the thalamus and the appropriate cortical column. The indirect pathway modifies this behavior by exciting the output nuclei and inhibiting the thalamus and cortical outputs. In our model, the direct pathway is involved in gating (through selective disinhibition) while the indirect pathway and other circuits regulate the selection process by controlling the amount of activation to scale to contextual factors controlled by the afferent cortical activity (similar to [Gurney et al., 2001]). Our model is consistent with known disease pathologies (such as decreased amplitude movements or tremors) in certain PD patients. The model makes specific predictions about the role of different pathways and circuits within the basal-ganglia and potentially offers computational explanations for the mysterious success of certain interventions (such as deep brain stimulation of the STN [Jankovic 2001] for PD).

We applied the model to data from normal, PD, HP and schizophrenic patients on the Wisconsin Card Sorting Test (WCST) to compare our model predictions to previous results [Amos 2000]. Since we were mainly interested in the role played by the basal ganglia, our model of the prefrontal cortex is similar in many respects to [Amos 2000]. As in this and most other models, we assume that particular prefrontal neurons exhibit sustained activation after a stimulus [Goldman-Rakik 1987]. We model both pyramidal and non-pyramidal cells, but assume that a majority of the cortical projections to the basal ganglia are excitatory. Finally, we assume a columnar arrangement of cortical neurons.

Results of our model on the WCST data suggested increased persevaration (with respect to card sorting strategy) for schizophrenic patients, erratic shifting of strategies for PD patients and a combination of errors for HD patients. While the overall results are compatible with previous efforts, our model predicts that the role of the basal ganglia is far more intricate than previously described. Our results showed that the complex dynamics

both from the modifying influence of the indirect pathway and from STN activity can have significant impact on the probability of shifting or maintaining the current card sorting strategy. In particular, our model predicts greater erratic errors for PD patients due to a combination of inappropriate matching at the striatum, as well as greater thalamic inhibition as a result of both the direct and indirect pathways. In HD patients with high neuronal death in the indirect pathway, the model predicts increased perseveration due to the enhanced inhibition of the STN (enhanced inhibitory input from GPE) and low striatal output. In HD patients where cell death progresses to affect the direct pathway, the model predicts erratic strategy selection as well. Our model also makes empirical predictions that match experimental evidence on different stages of HD and PD [Owen et al., 1997]. None of the previous models are able to make such detailed predictions.

Results from our model suggest that the basal ganglia may be involved in problem solving and planning that have complex dynamics and require prediction or simulation. To better understand the implications and evaluate our model, we are continuing efforts in the following directions: 1. Design cognitive tests for which our models of planning, working memory and executive control are likely to predict non-obvious results. 2. Apply these tests on subjects with and without diseases affecting relevant brain regions (PD,HD) and evaluate the model with respect to the results.

References

[Amos 2000] Amos, A., 2000. A Computational Model of Information Processing in the Frontal Cortex and Basal Ganglia, *Journal of Cognitive Neuroscience*, 12-3, 505-519, MIT Press 2000.

[Frank, et al., 2000] Frank, M., Loughry B., O'Reilly R. 2000. Interactions Between Frontal Cortex and Basal Ganglia in Working Memory: A Computational Model, *Institute for Cognitive Science,TR 00-01*, University of Colorado, Boulder, 2000.

[Goldman-Rakik 1987] Goldman-Rakik, P.S., 1987. Circuitry of primate prefrontal cortex and regulation of behavior by representational memory, *Handbook of Physiology - The nervous system*, 5, 373-417.

[Gurney et al., 2001] Gurney, K, Prescott, T. J., and Redgrave, P., 2001. A computational model of action selection in the basal ganglia. I. A new functional anatomy, *Biological Cybernetics*, 84, 410-410, 2001.

[Jankovic 2001] Jankovic, J., 2001. Surgery for Parkinson's disease, *Archives of Neurology*, V58, p. 970, December 2001.

[Middleton & Strick 2000] Middleton F. A. and Strick, P.L, 2000. Basal Ganglia Output and Cognition: Evidence from Anatomical, Behavioral, and Clinical Studies, *Brain and Cognition*, 42, 183-200.

[Owen et al., 1997] Owen, A.M., Iddon, J.L., Hodges, J. R., Robbins T.W., 1997. Spatial and Non-Spatial Working Memory at Different Stages of Parkinson's Disease, *Neuropsychologia*, 35, 519-532, 1997.

[Taylor & Taylor, 2000] Taylor, J.G. and Taylor N.R., 2000. Analysis of recurrent cortico-basal ganglia-thalamic loops for working memory, *Biological Cybernetics*, 82, 415-432.