Understanding decision dynamics in the basal ganglia under conflict and uncertainty

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Abstract:

The basal ganglia (BG) play a pivotal role in decision-making, facilitating selective attention through intricate interactions among its substructures. However, the relative contributions of these substructures to decision-making remain underexplored. We show that different BG substructures contribute to resolving uncertainty and conflict during perceptual decisions. Intracranial recordings from the subthalamic nucleus (STN), globus pallidus internus (GPi), and externus (GPe) in humans showed theta-band activities predictive of decision dynamics indexed by diffusion decision models with collapsing decision boundaries. Dynamic theta modulations predicted the onset and shape of the collapsing boundary: increased STN theta prolonged decisions under higher conflict, while decreased GPe theta expedited decisions under lower conflict. Moreover, conflict-induced response cautiousness was guided by STN under higher uncertainty but by GPe under lower uncertainty. GPi effects were uniform across conditions. These findings demonstrate the complex decision-relevant interplay amongst BG components.

Keywords: drift diffusion modeling; basal ganglia; computational psychiatry; cognitive control; neurocomputational slow-down dynamics

The basal ganglia (BG), a subcortical brain network, regulate the integration of decision-relevant information and determine the necessary evidence threshold for making a choice (Bogacz & Gurney, 2007; Shadlen & Newsome, 2001; Smith et al., 1998). Within the BG, the striatum accumulates evidence for alternative actions, while the globus pallidus internus (GPi) modulates the impact of these actions on decision-making (Doi et al., 2020; Moss et al., 2021; Westbrook et al., 2021). Additionally, the GPi's function is influenced by the globus pallidus externus (GPe) and the subthalamic nucleus (STN), which are integral to distinct pathways linking the BG and the cortex.

The STN's role as a global "brake" mechanism in response to decision conflict is supported by various studies across species, employing behavioral, functional imaging, and neural manipulation techniques (Aron et al., 2016; Herz et al., 2017; Isoda & Hikosaka, 2008; Moolchand et al., 2022; Schmidt et al., 2013; Wessel et al., 2019; Zavala et al., 2017). The diffusion decision model (DDM; Ratcliff, 1978) has been used to formalize the STN's contribution, suggesting that decision conflict elevates the decision threshold, leading to more deliberate and accurate responses. However, the relationship between STN function, decision thresholds, and decision conflict remains complex, with evidence suggesting dynamic rather than static decision thresholds regulated by the STN (Isoda

& Hikosaka, 2008; Moolchand et al., 2022; Ratcliff & Frank, 2012). Additionally, the role of the BG, in the presence of noisy and conflicting information, and the interaction between other BG structures like the GPe and GPi and their contribution to decision-making remains unclear.

Bridging findings across computational modeling of BG and behavior

We present a discussion on the distinct and complementary roles of STN, GPe, and GPi in decision-making, particularly under conditions of conflict and uncertainty. For doing so, we utilize a modified dot motion coherence task in which we independently varied conflict and evidence uncertainty. This task was administered with intracranial recordings to patients with Parkinson's disease (n=14) or dystonia (n=3). We then compared different DDMs with varying specifications of decision boundary dynamics and accumulation processes to identify the model that accounts best for observed behavior using Bayesian hierarchical modeling. Integrating single-trial local field potentials (LFPs) into the DDMs to account for time-varying dynamics, we relate trial-based theta band activity in BG components to latent decision features that are not directly observable with conventional analyses of RTs and choices.

Theta-induced modulation of decision boundary dynamics

A modified DDM with dynamic decision thresholds best captured task performance. This model included constant drift rates and a nonlinear decision boundary whose collapse was characterized by a Weibull distribution (Fig. 1) governed by two free parameters controlling the onset and the shape of this dynamic process. Incorporating trial-based theta responses into this Weibull-DDM, we found that early (post-stimulus) theta activity modulated collapse onset, whereas later pre-response activity modulated collapse shape.

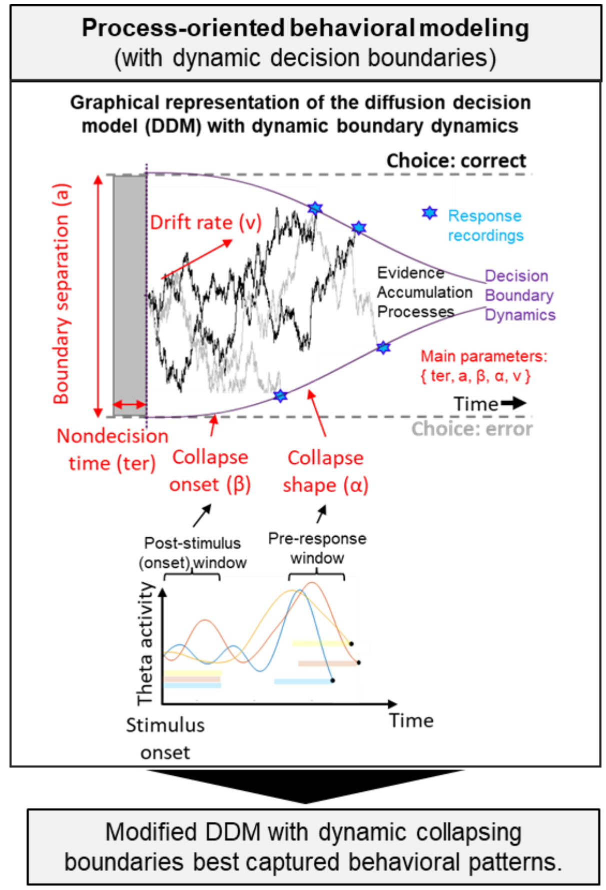

Figure 1: Weibull-informed decision boundaries of modified diffusion decision modeling.

Complementary decision dynamics between the STN and GP subsegments

Theta activity in distinct BG regions modulated the decision boundary collapses in a complementary fashion (Figure 2). Specifically, theta activation in the STN and the GPe modulated boundary collapses in opposing ways depending on uncertainty and conflict. In contrast, GPi theta activation was related to prolonged decision boundaries uniformly across task conditions. This is consistent with its role as the final output structure (Bogacz & Gurney, 2007; Frank, 2006).

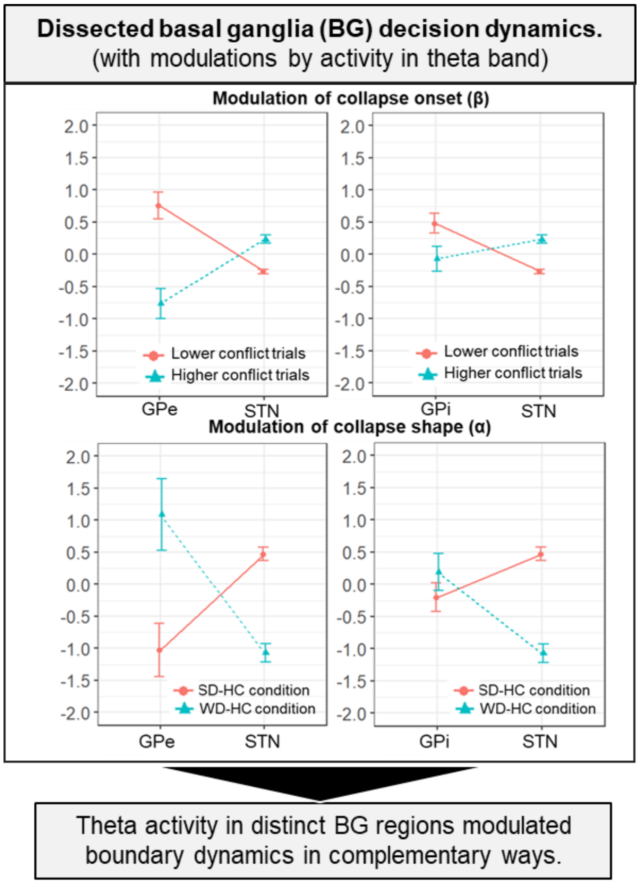

Figure 2: Complementary decision dynamics across three basal ganglia substructures.

Our study underscores the need for further investigation into the nuanced contributions of BG structures to decision-making, highlighting the importance of distinguishing between different types of conflict and uncertainty in future research.

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