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Why cognitive control matters in learning and decision-making

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Research in cognitive control and value-based decision-making both aim at explaining how agents achieve optimal behavioral outcomes, yet research in both fields has been conducted in separate and largely independent strands. Although cognitive control is typically investigated in perceptual decision tasks, a closer look at the mechanisms described by cognitive control theories shows their relevance for decision-making in general. These theories typically highlight that control is recruited by goals on various hierarchical levels (Koechlin and Summerfield, 2007), and that the brain recruits control processes based on monitoring of control signals that keep track of the state of goal achievement (e.g., conflict; Botvinick et al., 2001). The involved control processes and adjustments are manifold and range from changes in attentional or inhibitory control to the reconfiguration of mental states (e.g., task sets; Kiesel et al., 2010) that occur either reactively based on recent control signals or proactively driven by expectations of future control demands (Braver, 2012). The review articles in this section showcase various domains in which mechanisms of cognitive control support learning and decision-making, thus demonstrating the ubiquity of these mechanisms in cognition.

Frömer and Shenhav (2022) provide a comprehensive discussion of how control mechanisms contribute to the optimization of decision outcomes. They argue that goals shape the way value is represented in the brain, and that control processes act on these value representations in a similar way as they act on perceptual information. Control processes direct the flow of information within the value network so that neural activity indicates the expected value of different options in light of currently active goals. Monitoring is a central precondition for goal achievement and the efficient allocation of cognitive control. As potential control signals for both reactive and proactive control, the authors discuss a variety of variables, such as errors, surprise, conflict and confidence. Crucially, however, it is highlighted that those signals are most probably correlated and thus easily confused with value signals, calling for a diversification of paradigms and a finer-grained assessment of choice dynamics.

Whereas outcome value is often considered as a unidimensional variable, decisions in real world environments are associated with a mixture of appetitive and aversive outcomes. Yee et al. (2022) elucidate the computational and neural mechanisms by which these mixed motivational states guide control adjustments that maximize the net outcome. They argue that separate neural circuits link specific motivational states to corresponding control processes (e.g., behavioral activation and active avoidance associated with dopaminergic circuits, behavioral inhibition driven by serotonergic circuits), whereas the dorsal anterior cingulate integrates these expected outcomes to determine the strength and type of control adjustments. From their perspective, control adjustments can be reinterpreted as a motivated process involved in the continuous integration of outcomes to determine the optimal control policy (e.g., how much to attend to various sources of information or adjustments of the decision threshold). Motivational context and mixed motivation are identified as novel and critical dimensions in the endeavor to unravel the computational underpinnings of the evaluation and selection of control.

Knowledge of the generative rules of the environment is imperative for optimal decision-making and adaptive learning. However, those rules are not always obvious but must be actively inferred. Yu et al. (2021) invoke the notion of latent states, which contain relevant information about the generative rules of the environment. As latent states can change abruptly, adaptive learning requires constant monitoring for

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signals indicating these state changes. Here, a key role is played by surprise signals in sensory and domain-general brain regions that are conveyed to noradrenergic circuits which promote transitions to new latent states with new generative rules. Whereas these mechanisms are discussed within an adaptive learning framework, their central notions bear striking similarities with findings from the cognitive control literature. For instance, the authors interpret the P300 event-related potential as a correlate of state transition, while similar activity has previously been identified as a marker of control processes related to switching to new tasks (Karayanidis et al., 2010).

While most considerations so far have focused on neural processes implemented by an online (actively behaving) decision-maker, the brain also affords a rich toolset for offline purposes. For instance, during sleep and pauses from ongoing behavior, neural sequences of past experiences are reactivated. Wittkuhn et al. (2021) elucidate the extensive advantages that such a replay process possesses for adaptive learning and decision-making. Besides obvious functions such as increased learning and decreased forgetting of past experiences, replay also supports goal-directed behavior in a way that is often associated with proactive control mechanisms. For example, offline replay facilitates planning, e.g., by identifying relevant sub-goals, and can be used to make inferences about the structure of the environment as described in the previous paragraph, making it a versatile tool to facilitate reactive and proactive control during online decision-making.

These review articles provide a comprehensive picture of how central aspects of cognitive control – goals, control signals and control adjustments – are utilized to optimize learning and decision-making. Cognitive control is crucially necessary because decision-making is convoluted with dilemmas resulting from multifaceted and sometimes even conflicting goals. For example, in real-world environments, cause and effect relations are often known only to some extent. Whereas exploitation follows the goal of payoff maximization from known associations, exploration follows the goal of information maximization, investigating the yet to be known associations. Monitoring the need for control via diverse signals (e.g., surprise, confidence) is necessary to implement reactive and proactive control adjustments that trade off behavioral policies associated with these incompatible goals (Schulz and Gershman, 2019). Other dilemmas (e.g., cost-benefit, stability--flexibility, speed-accuracy) all pose similar conflicts between goals. This perspective on goal incompatibility affords an implicit notion of hierarchy, where low-level goals that make up the dilemma have to be arbitrated by a higher-level goal to solve this dilemma. The articles in this section of the special issue zoom in on different relevant aspects of this resolution process, offering novel and profound insights into the nature of decision-making and associated cognitive control mechanisms.

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