

Habits and goals: a motivational perspective on action control

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Two distinct systems govern the motivational control of action: first, cue-driven, outcome-insensitive habits, and second, value-based, goal-directed behaviors. These separate but interactive systems are based in distinct neural circuits — habitual behaviors are driven by a circuit of putamen-thalamic-motor regions, whereas value-based decision making relies on a top-down PFC-caudate network. This review highlights the recent advancements in behavioral science that investigate the motivational underpinnings of habits, situates contemporary behavioral methods into a framework of motivation, and identifies motivational aspects of habit-based pathologies. We also contextualize the recent literature on habits to highlight the necessity of improving our methods and promoting future research attempts to yield translational value (e.g. restoring flexibility in rigid habits).

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Current Opinion in Behavioral Sciences 2018, **20**:110–116

This review comes from a themed issue on **Habits and skills**

Edited by **Barbara Knowlton** and **Jörn Diedrichsen**

<https://doi.org/10.1016/j.cobeha.2017.12.005>

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Introduction

Motivation, in its simplest definition, is to be moved to perform an action [1]. This definition for motivational control brings forth a fascinating question: What is the driving factor that moves us to perform an action? Our actions can be shown to be motivated by two distinct systems: first, value-based, outcome driven goal pursuit, and second, cue-triggered, habitual control. For example, imagine checking your email app in anticipation of an important message after having heard the notification sound — essentially a goal-directed behavior driven by an evaluation of the outcome. This same action can also be performed out of habit, when the notification sound prompts the checking behavior, even in inappropriate contexts such as when driving. This motivation-based

distinction illustrates the dual action control system at work in guiding our behavior. Goal-directed behaviors are performed with the deliberate intent of attaining a valuable, desired outcome (e.g. important email). In contrast, habitual actions are driven by antecedent cues (e.g. the notification sound), such that an action can be executed despite the diminished value of the outcome (e.g. negative consequences of checking emails while driving) [2,3].

Our perspective of action control is based on distinct motivational systems; however, this is not the only dual-system account. Experiments investigating action control have focused on attentional factors [4], underlying memory systems [5], and more relevant to this review, motivational components [6]. In the attention literature, habits and goal-directed actions greatly overlap with the phenomena of automatic and controlled processing, where a controlled, reflective behavior is rendered automatic and less effortful with practice, such that performing a concurrent task will not impair its execution [4]. Similarly, other pioneering work in human behavior has attributed habitual and goal-directed control to be dependent on distinct memory systems. Accordingly, goal-directed actions fall under explicit memory processes, such as the declarative memory system of learned episodes and rules. On the other hand, habits are thought to be under the jurisdiction of implicit memory processes, notably the memory systems of skills and conditioning [5]. These memory-focused views were spearheaded by studies of medial temporal lobe (MTL) lesions in humans, in which patients' implicit memories remained intact, while explicit, episodic knowledge were largely impaired (for a detailed review and the evolution of the memory system approach, please see [7], and for a distinction of skills and habits, see [8]). There is certainly overlap between these accounts, as cue-driven habits are usually also automatic and dependent on implicit memory. However, the motivational account of action control focuses on the attribution of the motivational origin of actions to value-based goal pursuit versus cue-triggered habitual control [3,6]. For example, one difference stemming from the motivation perspective is that a goal-directed, value based behavior can operate via a caudate-dependent response–outcome association, which does not necessarily rely on the explicit episodic and semantic, hippocampus-driven processes emphasized in the memory literature.

In brief, our motivational perspective on action control attributes goal-directed behaviors to be driven by a desirable outcome, and as we unpack further in this review,

goal-directed response–outcome learning has been shown to be primarily dependent on the caudate nucleus, which lies in the dorsal striatum. In contrast, habitual control is driven by a salient cue, a stimulus–response process associated with the putamen, another subregion of the dorsal striatum [9]. Indeed, in probabilistic categorical learning tasks, optimal goal-directed performance relies on associative response–outcome contingency learning rather than declarative memory processes [10]. In the ‘weather prediction’ version of these paradigms, subjects learn to categorize series of abstract cards to predict sunny or rainy weather by distinguishing stimulus patterns and mapping them onto outcomes. The categorization process here could be framed as an outcome-driven, goal-directed behavior, as subjects perform instrumental responses in pursuit of an accurate categorization outcome. In fact, amnesic patients perform comparably to neurotypicals in response–outcome learning of these probabilistic categorizations [11], supporting the assertion that goal-directed control is not always dependent on declarative, hippocampus-driven systems — rather, it is primarily a caudate-regulated process that may be difficult for the learner to explicitly verbalize, and even survives hippocampal injury [10,11]. Nevertheless, it is important to note that these striatal and hippocampal memory systems are known to interact to guide learning, lending support to the notion that goal-directed and habitual behaviors do not always fit neatly into a declarative versus non-declarative dichotomy [12].

Distinguishing cue and value driven actions

The distinction between habits and goals is established by assessing whether the behaving agent considers the outcome value when planning an action, or is reflexively motivated by the preceding cue. To test whether the action is cue or value driven, researchers have primarily relied on paradigms in which the outcome value of a learned response is changed. For example, imagine that the participant learns two stimulus–response–outcome associations, where the stimuli are cues that precede a particular instrumental response (e.g. left or right button press), which predict different rewarding outcomes. Following training on these stimulus–response–outcome sequences, the behavior is tested to detect whether it is governed by the value of the outcome (i.e. a response–outcome association), or the salience of the stimulus (i.e. a stimulus–response association). In humans, this simple operant conditioning based task structure has been used with primary rewards (e.g. food), where the food outcome is devalued through selective satiety (i.e. participant eats one of the food outcomes until it is no longer pleasant, diminishing its perceived value). Relative to the cue signaling the still-valued outcome, persisting responses made to the cue signaling the devalued outcome in the subsequent test phase indicate habitual control [13–16].

Whereas we have focused on motivation in terms of what governs or directs behavior (i.e. whether the source of

action is an incentive, or a cue that triggers a reflexive habit), other motivational accounts of action control have also emphasized a more general ‘energizing’ effect of motivation, which increases the vigor at which the agent performs an action [17]. Changes in this generalized motivation, due, for example, to changes in hunger, do affect the vigor with which a habit is performed, without affecting action choice [17]. However, vigor is not thought to promote habit acquisition. One of the crucial factors in habit formation is the schedule in which the reward is administered, with variable-interval reinforcement schedules promoting habit formation more than variable-ratio schedules [18]. Response rate and reward frequency are decoupled in a variable-interval reinforcement schedule, leading to lower response rates [19,20], and although the salience of a desirable outcome may increase response rate, this increase is not known to facilitate outcome-insensitivity [21]. Thus, although response frequency may be a robust indicator of motivation, it is not thought to play a key role in facilitating habits.

The balance between goal-directed and habitual control has also been examined using secondary rewards (e.g. money or points) in deterministic paradigms [22]. In these studies, the agent must learn the associations between the visual stimulus, the instrumental response, and the monetary outcome, but later readjust the behaviors per the experimenter’s instructions to continue earning money or prevent losses. In one example, visual cues of closed boxes distinguished by pictures (stimulus) are associated with right or left button presses (response). Correct responses yield another picture paired with money (outcome). Otherwise, an empty box is shown. In a subsequent devaluation phase, the subject is informed that some of the outcomes will no longer be paired with money. The subject must only choose the response that previously produced the still-valued outcome, allowing the experimenters to test response–outcome strength. Furthermore, to determine the balance of goal-directed and habitual control, a slips-of-action phase follows. The subject is shown which outcomes are now devalued, and instructed to only respond to the cues predictive of still-valued outcomes in a Go/NoGo task. Examining the balance in the dual system may reveal whether habits manifest as a result of a strengthening in habitual control (i.e. agent performs well when a stimulus–response strategy is optimal), impairments in goal-directed control (i.e. the agent is unable to persevere when a response–outcome strategy is optimal), or both [23,24].

Several labs have approached habits using sequential decision making paradigms to further understand mechanisms of decision making. These tasks utilize reinforcement learning algorithms to determine whether choices account for mere history of reward (model-free),

or more complex cognitive models of the environment (model-based) [25]. Typically, the subject must choose between two stimuli on each of the two steps of the decision making sequence. At step 1, the subject's choice between two stimuli transitions the trial into the next step. At step 2, depending on the previously chosen stimulus, the subject sees either a commonly occurring or a rarely occurring pair of stimuli, and again decides between the two stimuli. The choice at step 1 dictates with high or low probability which stimulus pair will appear at step 2, and the choice at step 2 yields either a reward or no outcome. If the subject considers the probabilities of the stimulus pair occurrences, s/he will make the optimal decision sequences even after a rare reward omission. If the subject makes decisions based solely on reward receipt, the decision sequence that produced the rare reward will be repeated in a subsequent trial, and similarly, the optimal decision sequence will be abandoned if it results in a rarely occurring reward omission. Participants are thought to behave habitually if they select recently rewarded actions rather than rely on the cognitive model of the task, potentially leading to these suboptimal choices (hence the label 'model-free'). In contrast, if the individuals account for the probability of reward receipt from each choice, selecting actions according to their representation of the task structure (i.e. cognitive model of decisions and corresponding outcome probabilities), they are thought to be goal-directed, or 'model-based'.

Discordance in contemporary methods

The model-based strategy requires sophisticated characterization of each response–outcome contingency within the task, and tracks the value of choices based on associated reward probabilities. Thus, the model-based strategy fits well onto the framework of our motivational control of action perspective. Similar to goal-directed behaviors that are performed in pursuit of a desirable outcome in operant conditioning paradigms, model-based decision making resembles a system that is goal-directed and driven by outcome values. However, it can be argued that the model-free decision making strategy still takes into account the outcome value of an action, thus not fitting the cue-driven component of our view of action control. A model-free strategy considers history of reward receipt, and promotes actions in accordance with recent gains. In support of this point, a cross-validation of the aforementioned deterministic monetary reward tasks and these sequential decision tasks shows evidence of a goal-directed and model-based agreement. However, this correspondence is absent between habitual and model-free performance [26^{*}]. Nevertheless, these tasks have benefitted the literature tremendously, and offer corroborating evidence for many points regarding habits and goals in this article (for further discussion regarding these paradigms and their roles in this translational domain, see [27]).

Cortico-striatal connectivity is crucial for regulating action control

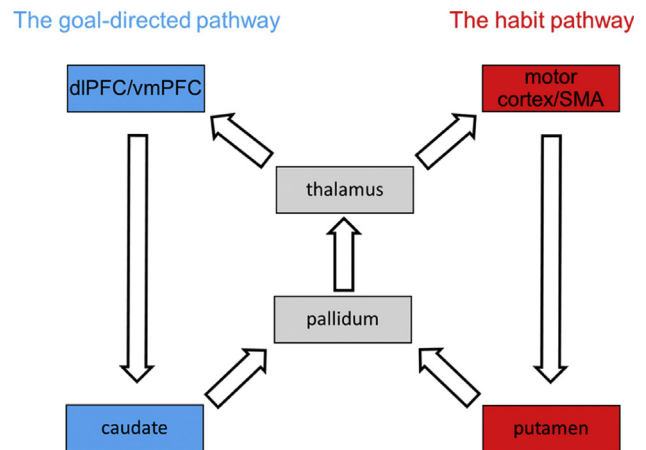
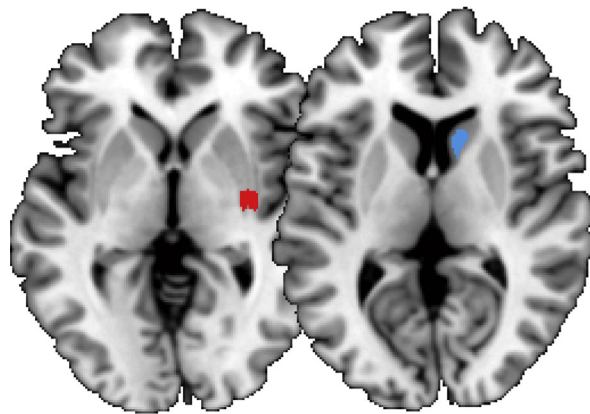
The neural systems of value-based and cue driven actions show substantial overlap with anatomically distinct cortico-striatal pathways in the brain. Situating the motivational account of action control to the cortico-striatal circuitry is well-supported by cross-species evidence in the habit literature. Specifically, a plethora of rodent and human data highlight a top-down, prefrontal input on the striatum, illustrating a conservation of brain systems across species. The rat dorsolateral striatum (homologous to the posterior putamen in humans), has been established as a critical area for cue-triggered, habitual control, due to its thalamic and motor cortex connectivity [28,29]. On the other hand, the posterior dorsomedial region of the striatum (homologous to the caudate), which has strong connections to the prefrontal cortex (PFC), is known to regulate value-motivated, goal-directed behaviors [30,31], as depicted in Figure 1 (for a recent discussion and reevaluation of these assertions, please see [32]).

Recent human neuroimaging studies present converging evidence confirming the involvement of the cortico-striatal pathways in driving motivated actions. As an integral part of the reward circuitry, the PFC may be involved in the top-down control of motivational control because of its role in indirectly inhibiting the cue-reactive sensorimotor striatum. Both structural and functional connectivity between the caudate and ventromedial prefrontal cortex (vmPFC) predict goal-directed actions, and habit-like behaviors are correlated with increased posterior putamen volume and white matter tract strength with premotor cortex [33–35]. In line with this argument, response–outcome related processes (e.g. execution of actions guided toward valued outcomes) show evidence of heightened dorsomedial and vmPFC recruitment [36]. Causal inferences have also been made in identifying candidate regions for goal-directed and habitual action regulation. Multivariate pattern classification of functional MRI data suggests that the putamen region contains stimulus–response information, whereas the response–outcome information is contained in the caudate, vmPFC, and dorsolateral PFC (dlPFC). The stimulus onset functionally predicts activation patterns across a putamen, thalamus, and premotor cortex network, solidifying the thesis that these stimulus driven habits are regulated by a dorsolateral striatum–motor cortex cooperation, similar to that of the rat [37^{**},38]. Similarly, recent efforts in investigating lesions of the vmPFC identify this area as indispensable for value-based decision making, such that damaged vmPFC gray and white matter impairs goal-directed control, while leaving habitual actions intact [39].

Deficits in goal-directed control are evident in neural abnormalities

If value-based decision making and cue-driven habits are regulated by distinct brain regions, the inability to

Figure 1



The cortico-striatal pathways driving goal-directed and habitual control. Left: The posterior part of the putamen, highlighted in red, due to its connections with the motor cortex (e.g. supplementary motor area, SMA), is a critical region for the execution of habitual actions. The caudate, highlighted in blue, due to its input from the prefrontal cortex, plays a major role in value-based, goal-directed behaviors. The MRICron software (URL: <http://www.mccauslandcenter.sc.edu/mricro/mricron/>) was used to obtain axial slices of the brain at $z = 0$ for the putamen, and $z = 8$ for the caudate. Right: A simplified schematic of the cortico-striatal loops that regulate goal-directed and habitual control. Goal-directed actions rely on connectivity between the prefrontal cortex and the caudate, whereas habitual actions are regulated by a network of putamen and motor regions. These distinct action control systems share the pallidum and thalamus in relaying information from the striatum for action execution. dlPFC: dorsolateral prefrontal cortex; vmPFC: ventromedial prefrontal cortex.

consider outcome values in action execution should reflect abnormal structural and functional patterns. For instance, habitual alcohol abusers exhibit distinct neural patterns of PFC hypoactivation along with an impairment in model-based decision making strategies [40]. Healthy participants of high trait impulsivity display more model-free control in a sequential decision making task, a finding contrasted by model based, goal-directed control predicting higher gray matter volume in the dlPFC [41]. Similarly, stress is a physio-environmental factor that reliably promotes habitual control at the expense of value-based decision making, and impairs prefrontal sensitivity to outcome values [42,43]. Long-term stress is known to affect action control in a manner that favors habitual control, while leading to heightened recruitment of the putamen. Strikingly, these behavioral and functional patterns are also associated with fascinating structural abnormalities. Individuals with long-term stress exhibit abnormal increases in putamen volume, and atrophy in the caudate and medial orbitofrontal cortex [44**] — a sub-region of the vmPFC often characterized by its role in valuation [13,45]. These aberrant behavioral, functional, and structural patterns are reversed when no longer stressed, underlining the tangible brain representations of motivational control and their reactivity to stress [44**]. Furthermore, an investigation of the developmental trajectory of action control reveals that goal-directed control is incrementally recruited throughout development, possibly as a consequence of heightened cognitive resources that become available with neural maturation [46], facilitating efficient value-driven goal pursuit. Further evidence that a shift in motivational control relies

on the degree of prefrontal influence on the subcortical brain comes from studies showing that the dlPFC, when deactivated, renders goal-directed behaviors habitual [47*], and that executive control predicts intact model-based strategies [48*].

Compulsion-driven pathologies impact value-based decision making

An imbalance in motivational control may manifest as compromised behavioral flexibility and dysfunctional neural patterns in clinical magnitudes. For instance, disorders of compulsion, such as Obsessive-Compulsive Disorder (OCD) [49], alcohol abuse [40,50–52], cocaine dependence [53,54], various other stimulants and opioid addictions [55], Tourette's Syndrome [56], and even non-clinical symptoms of compulsive tendencies [23] predict cue-reactive habitual control at the expense of goal-directed decision making. In these habit-dominated, compulsion based disorders, unfavorable actions prevail despite unpleasant, disadvantageous outcomes. Intuitively, the proclivity to behave habitually (e.g. ritualistic behaviors triggered by obsessive thoughts in OCD, or drug use driven by salient drug-associated cues) may very well arise from dysfunctional motivational circuitry in the brain, as evidenced by neural investigations of these disorders [49,50,54,57] (for a detailed review on the cortico-striatal patterns in alcohol dependence, see [58]). In sum, optimal decision making relies on a balance between cue and value based systems, and an imbalance in these components may result in disorders favoring habitual control, paralleled by dysfunctions in the cortico-striatal pathways. However, it should be

noted that because action control relies on facets of motivation, attention, and memory, it is not yet clear which of these processes are the primary targets of impairment in these disorders.

Conclusions and future directions

As we have outlined here, habits are reflexively triggered by cues and are less taxing on cognitive resources, but as a caveat, they are difficult to override and are susceptible to errors in maximizing gain. In contrast, goal-directed behaviors are deliberate, and are performed with the values of the outcome in consideration. These distinct motivational systems are differentially represented in the brain, where cue-driven actions rely on a striatal-thalamic-motor circuit, and value-based decision making imposes a top-down control over behavior, regulated by cortico-striatal pathways. A variety of disorders alter the physiology and anatomy of cortico-striatal pathways, primarily leading to habitual actions at the expense of value-based, goal-directed control.

Although habitual control is imperative for efficiently interacting with our environment (e.g. imagine having to reflect on the meaning of a red traffic light instead of habitually stopping), the prevalence of habit-based disorders illustrates the importance of behavioral flexibility. Contemporary research has mainly focused on circumstances or disorders in which goal-directed control is shifted toward habits. However, there is a striking absence of research that investigates this shift in the other direction—how do we render existing habits goal-directed? For example, can short-term manipulations geared toward solidifying intentions in planned actions [59] generalize to restoring goal-directed control? Furthermore, having contrasted our motivational view of habits with other contemporary perspectives, a question that arises is, are we approaching the study of habits in humans in the most effective manner? Although fruitful, the tasks we have described here in the domain of devaluation via selective satiety, explicit instruction, or sequential decision making, could be built upon to better capture action control.

Subjectivity of primary reward value, ecological validity of instrumental tasks, some discordance in the literature in what constitutes a habit, and the difficulty in transforming rodent models to human studies have been concerning caveats of current paradigms [26*,27]. For instance, a disadvantage of using primary reward devaluation in humans is relying on self-reported selective satiety to confirm that the subject indeed perceives a reward as less valuable after feeding. Although effective in rodents, because of factors such as demand characteristics and variability in reward palatability, selective satiety may be a less optimal procedure for detecting habits in humans. In a recent contribution to the arsenal of tasks that parse habits and goals, devaluation related shortcomings are ameliorated by employing contingency

change rather than outcome devaluation in a visuo-motor stimulus–response task [55]. In this study, subjects were trained on stimulus–response associations for two days, rendering these contingencies familiar. A novel set of stimuli were then introduced, and eventually the stimulus–response contingencies for both stimulus sets were changed, such that the familiar and novel stimuli required different button presses. If a habit is formed to the familiar stimulus, the contingency change should produce more perseverative errors in the familiar set than the novel set, serving as an effective assay of habitual control. In short, enhancing the contemporary tools used in habit research, and directing efforts toward examining habit disruption, will be invaluable for translating our understanding of action control mechanisms into tangible applications for effective intervention methods.

Conflict of interest statement

Nothing declared.

Acknowledgements

The authors would like to thank Michael Shiflett and the Tricomi Lab for their valuable comments throughout the preparation of the manuscript. AOC and ET were supported by funding from the National Science Foundation (NSF BCS 1150708) and a Rutgers University-Newark Chancellor's Seed Grant for New Initiatives.

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This study shows evidence of a direct link between executive function and motivational control of action. The protective effect of working memory capacity on action control is robust enough that the deleterious effects of stress are normalized. This study reports fundamental principles that may be used in possibly remediating maladaptive habitual control in future attempts.

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