Interactions of motivation and cognitive control
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There is general agreement that both motivation and cognitive control play critical roles in shaping goal-directed behavior, but only recently has scientific interest focused around the question of motivation–control interactions. Here we briefly survey this literature, organizing contemporary findings around three issues: (1) whether motivation preferentially impacts cognitive control processes, (2) the neural mechanisms that underlie motivation–cognition interactions, and (3) why motivation might be relevant for overcoming the costs of control. Dopamine (DA) is discussed as a key neuromodulator in these motivation–cognition interactions. We conclude by highlighting open issues, specifically Pavlovian versus instrumental control distinctions and effects of motivational valence and conflict, which could benefit from future research attention.

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Introduction
There has been a longstanding interest in investigating motivation and cognitive control as modulators of goal-directed behavior. However, only recently have researchers begun to examine these two processes in terms of their integrated influence on behavior and the brain [1,2•]. Here we review recent studies on motivation–cognition interactions, while highlighting key unresolved issues in this burgeoning domain.

The challenge of operationalizing motivation
René Descartes once contended that the 'passions' in human nature 'dispose our soul to want the things that nature decides are useful for us, and to persist in this volition; and [to bring about] the agitation of the spirits which customarily causes them to dispose the body to

those movements that help bring about those useful things [3].' Although to modern ears this quotation initially seems overly baroque, upon deeper inspection it reveals a surprisingly apt description of what could be considered the four central dimension of motivation: value/utility (things of use), anticipatory affect (passion, desire, and persistence), activation/energization (agitation of the spirits), and directed action (disposing the body to movement).

In the scientific literature, motivation has been characterized as the energization and direction of behavior, response vigor, arousal and intensity of motor output, or as a biologically-driven impulse that compels an organism to act [4–7]. Since the concept of motivation was created to provide a theoretical framework to describe a diverse range of behaviors (e.g., approach, avoidance), a precise operationalization of this multifaceted construct has proved to be challenging. Despite valiant efforts, researchers have yet to agree upon a unified definition and comprehensive framework for this elusive construct [7,8].

Nevertheless, the term 'motivation' is consistently used to describe when an external or internal incentive alters the biological system (i.e., generates a 'motivated state') to stimulate an observable change in behavior. It is generally assumed that providing incentives (e.g., offering rewards or threats/penalties) can induce such motivational states, which then lead to dynamic adjustments in cognitive processing, and consequently, influence behavior. However, open questions remain regarding the mechanisms that underlie such motivation–cognition interactions.

A further point to acknowledge is that motivation has been found to influence a broad range of cognitive processes, that is, attention [9,10], learning [11,12], memory [13,14], and perception [15,16]. Here, we emphasize studies that have examined motivation as it relates to cognitive control, a key interaction underlying goal-directed behavior.

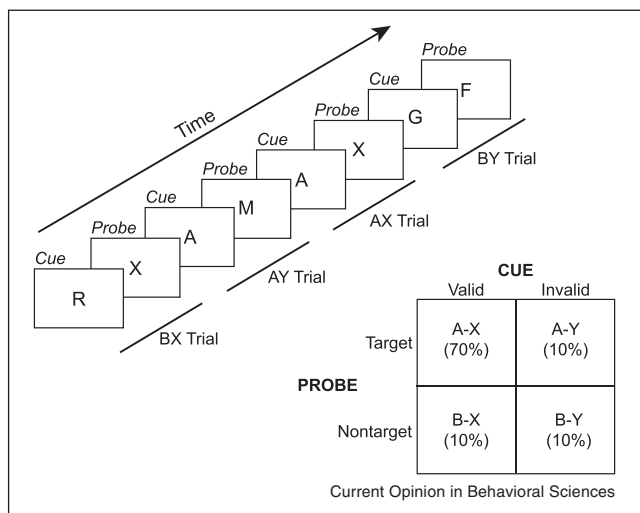## The interactions of motivation and cognitive control
The recent literature in this domain can be organized around three central questions. First, is there evidence that motivation selectively enhances cognitive control? Second, what are the neural mechanisms that give rise to these interactions? Third, why is motivation relevant for overcoming costs of cognitive control?

Selective motivation–cognitive control enhancements?

The claim that motivation preferentially impacts tasks with higher cognitive control demands is compelling and provocative [2•]. Demonstrating it would require two steps: (1) isolation of a selective measure of cognitive control and (2) showing that this measure is significantly enhanced under high motivational value conditions (e.g., when incentives are offered). Some tasks include selective behavioral measures that isolate control processing, such as task switching, conflict paradigms (e.g., Stroop, flanker), response inhibition tasks (e.g., go/no-go, stop signal) and context processing paradigms (e.g., AX-CPT). In task-switching paradigms the control measure is the mixing or switching cost (i.e., switch–no switch), while in the Stroop and flanker tasks it is the interference effect (i.e., incongruent–congruent), and in the stop-signal task it is the stop-signal reaction time (i.e., time required to inhibit an initiated response). Finally, in AX-CPT tasks, cognitive control is indexed by performance on AY and BX lure trials (Figure 1).

Monetary incentives appear to enhance cognitive control performance via increased proactive control — the utilization of preparatory tasks and/or contextual cues to increase accuracy and reduce response times

Figure 1

Schematic of classic version of AX-CPT paradigm. Single letters are visually displayed as a series of cue-probe pairs. Here, the target pair is the occurrence of an X probe followed immediately an A cue. Of the three nontarget trial types, BY trials (where B refers to any non-A cue and Y refers to any non-X probe) provide a low-demand baseline general performance index, while BX and AY serve as low-frequency lures that selectively index cognitive control (each lure type typically occurs with 10% frequency). A range of studies with this paradigm have found that optimal utilization of contextual cues can eliminate typical interference effects observed in BX trials, because in these trials the contextual cue allows for fully accurate preparation of a non-target response [74–76]. By contrast, enhanced proactive control increases interference on AY trials, since contextually based preparation of a target response is invalid in these trials.

[17••,18,19]. Recent studies have observed that anticipation of reward incentives selectively reduces switch costs in task-switching paradigms [20,21]. Likewise, Chiew and Braver (2016) found that task-informative cues in the flanker task (indicating whether an upcoming trial was incongruent) could reduce interference effects, but only when cues were combined with rewards and sufficient preparation time [17••]. Thus, reward incentives seem most effective in modulating cognitive control in a proactive and preparatory manner [22•].

However, motivational enhancements of proactive control can both benefit and impair task performance. This phenomenon has been most directly examined within the AX-CPT paradigm [23–25,26••]. Hefer and Dreisbach (2017) observed that reward motivation manipulations led to persistent increased use of contextual cue information, even under conditions which result in sub-optimally high AY errors (i.e., reduced BX interference but increased AY interference) [26••], providing evidence for both costs and benefits of reward motivation on proactive control.

Others have found that motivational incentives enhance reactive control (i.e., rapid adjustment of control in response to performance monitoring). Boehler et al. (2014) observed that rewards speeded up response inhibition in a stop-signal task without preparatory cues, revealing that rewards also facilitate inhibitory responding, even when proactive mechanisms are likely not engaged [27••]. More research is needed to determine the relevant boundary conditions for when motivational manipulations will result in proactive versus reactive control enhancements.
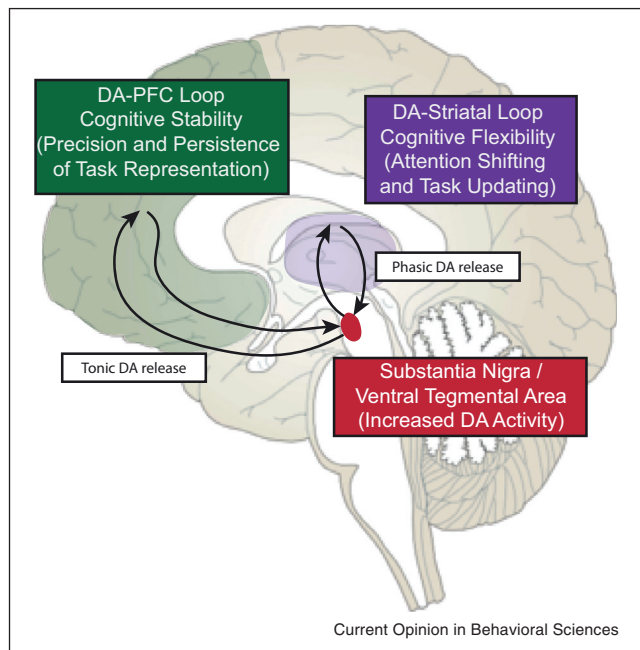
What are the neural mechanisms by which motivation impacts cognitive control?

Dopamine (DA) is hypothesized to play a key role in motivation–cognition interface [28], with tonic DA activity postulated to mediate the relationship between average reward and movement vigor [29,30]. Movement vigor appears to reflect a general arousal process, which leads to quicker responding in a high reward context, and has been considered a characteristic behavioral measure of motivation [31,32]. Rigoli and colleagues (2016) examined this hypothesis in a visual search task in which participants received monetary rewards which varied block-wise ($1, $6, $11), independent of a $3 reward earned for accurate performance within each trial [33••]. Higher average reward (manipulated across blocks) was associated with increased motor vigor (measured by button pressing force). These effects were mediated by activation in subcortical brain regions with high DA neuronal concentration, bolstering the role of DA as critical in regulating movement vigor. However, increased vigor in higher reward contexts may not directly entail selective enhancement of cognitive control mechanisms (e.g., vigor may alternatively reflect priming of the motor systems).

Another hypothesis is that motivated cognitive control arises from DA modulation of both striatum and PFC via parallel neural pathways (Figure 2). Cools (2016) hypothesized that PFC DA facilitates stabilization of current goal representations (via tonic DA release), whereas striatal DA disrupts these representations via attention shifting and/or task-set updating in response to unexpected relevant stimuli (via phasic DA release) [34•]. This dynamic tradeoff between cognitive stability and flexibility [22•] may explain the sometimes paradoxical detrimental effects of monetary rewards on cognitive control, as both excessive and insufficient PFC DA may impair the ability to maintain task representations in working memory over time (i.e., U-shaped DA effects) [35–37].

Interactions between motivational signals from dopaminergic midbrain and PFC consistently enhance cognitive control [38,39], and may even selectively target specific levels of cognitive control hierarchy in lateral PFC (e.g., posterior-to-anterior gradient corresponding to task rule abstraction). Bahlmann and colleagues (2015) found evidence consistent with this idea, and observed that the strongest motivational effects in lateral PFC corresponded to mid-level task representations, which were

Figure 2

Dopamine (DA) may have differential effects on motivated behavior. It has been hypothesized that tonic release of DA in the prefrontal cortex (PFC) may facilitate the precision and persistence of current task goal representations (i.e., cognitive stability). By contrast, phasic release of DA in the striatum may facilitate attention shifting and updating of task goal representations based upon unexpected, behaviorally important stimuli (i.e., cognitive flexibility). Tonic DA is also hypothesized to mediate the relationship between reward rate and response vigor in tasks, although the neural pathway of such effects has not been well investigated (not shown in figure).

accompanied by increased functional coupling between the DA midbrain and lateral PFC [40••].

However, the exact mechanism by which motivation enhances control remains unknown. One hypothesis is that motivation improves the signal-to-noise ratio in the neural coding of task rules within PFC, thus increasing the efficacy and precision of cognitive control performance. Such an account would be consistent with classical experimental and computational studies of DA effects on PFC activation [41–45]. Etzel et al. (2015) reported data consistent with this account, as they used multivariate pattern analyses to decode task representations on a trial-by-trial basis under reward motivation manipulations. There, incentives not only sharpened task representations in frontoparietal cortex (i.e., more discriminable voxel patterns in each task), but also increased task decoding accuracy, with the latter statistically mediating improvements in task performance [46]. Together, these studies suggest that motivational incentives impact cognitive control via dopaminergic signaling to frontoparietal control network, thus facilitating more effective, stable, and precise task representations.

Why is motivation relevant for overcoming the costs of cognitive control?

Cognitive control, specifically utilizing cognitive resources in the service of decision-making, is intrinsically costly [47,48]. The term 'cognitive effort' typically refers to the subjective experience of up-regulating the cognitive control system during goal-pursuit, and is often considered to be a canonical metric for the cost of cognitive control engagement [47]. Individuals are less willing to engage in cognitively demanding tasks if the allocated effort costs outweigh the expected benefit [49–51].

Motivation may act as a modulatory factor that offsets these effort costs. Manohar and colleagues (2015) proposed a computational framework which argued that motivation improves task performance beyond normal bounds (e.g., faster and more accurate/precise choices in motor and decision tasks) [52••]. Thus, task performance can be improved without contravening the speed-accuracy trade-off. However, missing from this framework is an explanation of why cognitive control is costly to begin with. One speculation is that recruiting cognitive control detracts from available cognitive resources in a limited capacity system, thus representing an opportunity cost [53•]. Importantly, what makes such costs 'expensive' or 'cheap' depends on whether using that resource involves forgoing another beneficial use or not, respectively.

These ideas are consistent with the *Value-Based Cognitive Control (VBCC)* framework, which posits that engaging cognitive control can be construed as an economic decision between the estimated subjective/computational costs of control weighed against the expected benefits

of enhanced control [54]. Broadly, VBCC opens up a novel domain of quantifying effort, and argues that motivation and cognitive effort are juxtaposed: higher motivational value can offset higher effort costs in shaping control policy selection and behavior. In other words, appetitive motivation should increase the subjective value of the current option, thus decreasing the opportunity cost of exerting cognitive control to obtain it. Conversely, aversive motivation should offset potential benefits of reward, such that a negative option should decrease cognitive control engagement.

In this framework, DA is theorized to modulate the efficacy of control through titration of the precision and persistence of task representations [55]. Precision refers to the clarity of the task goal representation in the brain (i.e., sharpness, signal-to-noise ratio), whereas persistence refers to the duration over which these task goal representations are actively maintained (i.e., sustained elevations in neuronal activity). Because of the well-established limited capacity of active goal maintenance, the degree to which an individual commits to representing a task goal clearly and persistently incurs an opportunity cost, that is, they forgo the chance to use those cognitive resources for alternative tasks. Thus, motivationally triggered DA release in the PFC should facilitate goal-directed task performance and reduce control costs.

Although these ideas regarding the role of DA in motivating cognitive control have been laid out conceptually [56•], there is still a lack of convincing experimental support. The most direct evidence would be to demonstrate a multi-way link between increased motivational value, increased DA release and neural changes within PFC, which together mediate improvements in behavioral cognitive control measures. Such evidence may be hard to obtain with current neuroscience methods, but a potentially promising route is to utilize simultaneous PET-fMRI to co-localize changes in DA release (via radioligand binding) with changes in PFC BOLD activity.

Open issues
In our opinion, two important factors require further investigation to make progress in this domain: (1) Pavlovian versus instrumental influences of motivational incentives; and (2) effects of motivational valence and conflict.

Pavlovian versus instrumental effects of motivational incentives
The dichotomy between Pavlovian versus instrumental control of behavior has long played an influential role in the study of motivation [57], but researchers have only recently started to examine this distinction in terms of effects on human decision-making [58,59•]. Pavlovian control refers to a behavioral reflex elicited by predictive stimuli associated with appetitive or aversive outcome (e.g., approach, withdrawal), while instrumental control refers to learning of the stimulus-dependent contingency between responses and outcomes (e.g., a rat must press a lever to earn a food pellet reward). Thus, in instrumental paradigms, motivational incentives are typically used to reinforce or punish behavioral responding (e.g., presenting food pellets will increase lever pressing, whereas presenting shocks will decrease lever pressing).

Researchers have attempted to disentangle these dissociable influences in simple decision tasks (e.g., stimulus–response associations, go–no-go tasks) [60]. Some have proposed that instrumental responses are unsigned and therefore not sensitive to the valence of the motivational incentive driving the behavior, whereas Pavlovian conditioned responses are evolutionarily hard wired and thus explicitly linked to incentive valence [61]. These distinct mechanisms appear to have orthogonal effects in modulating simple decisions, with instrumental influences giving rise to more specific enhancement of behavioral responding, whereas Pavlovian influences may lead to a general excitatory or inhibitory bias on instrumental responding (Figure 3a).
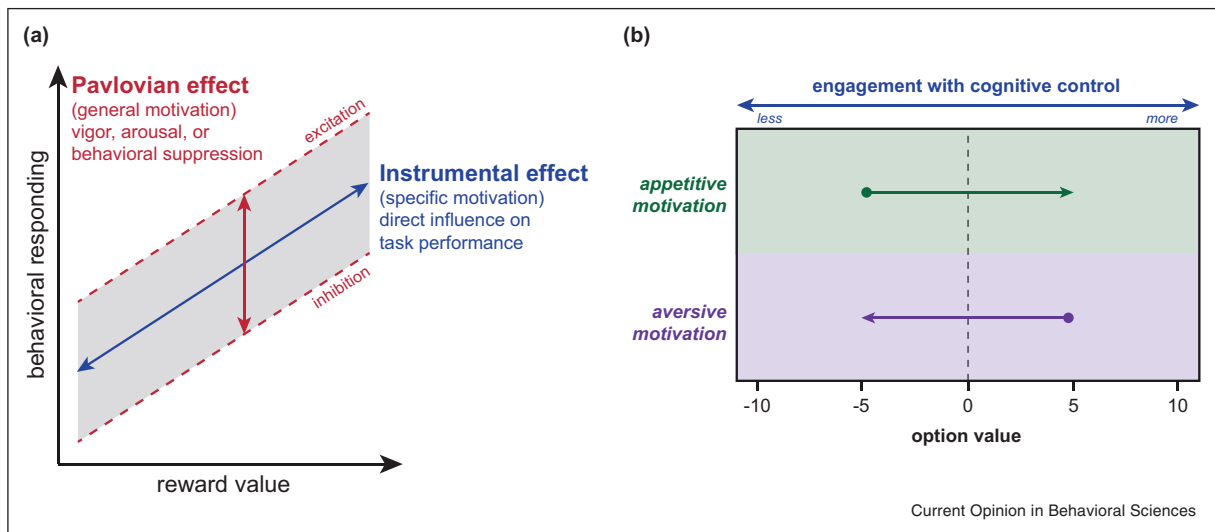
However, it remains ambiguous whether motivational enhancements of cognitively controlled behavior might reflect Pavlovian as well as instrumental mechanisms. One approach for investigating this question would be to use well-established Pavlovian Instrumental Transfer (PIT) paradigms [62], although to date these have not been examined within the context of motivation–cognition interactions.

Valence and motivational conflict
Although motivational incentives are inherently valenced (e.g., appetitive, aversive), surprisingly few studies have examined this dimension in motivation–cognition interaction studies. Moreover, a broader unanswered question is how control processes are modulated by motivational conflict (i.e., integration of both appetitive and aversive incentives) [63,64].

A recent novel design developed by Yee *et al.* (2016) highlights these issues within the context of a cued task-switching paradigm [65], in which individuals must exert cognitive control to earn money, but are provided with liquid incentives of differing valences (e.g., appetitive, neutral, aversive) as task performance feedback [66••]. Motivational conflict occurs in the aversive liquid block, as subjects must integrate the prospect of saltwater delivery (as performance feedback) with potential monetary earnings in deciding whether to enhance cognitive control and maximize reward rate. The parametric effect of these bundled incentives suggests that humans indeed integrate different incentives into a net motivational value that modulates cognitively controlled

Figure 3

(a) Reward incentives may have parallel effects on motivation and behavioral responding via both Pavlovian and instrumental control influences. The Pavlovian effect may reflect a general motivation mechanism, such that the valence of an incentive biases responding in an overall excitatory (e.g., arousal, vigor) or inhibitory manner (e.g., behavioral suppression). Instrumental influences may implement a more directed motivation mechanism (e.g., specific enhancement of task performance). These two effects may occur simultaneously and alter behavioral responding via parallel mechanisms, but this distinction has not yet been fully explored within the context of cognitive control. **(b)** The engagement of cognitive control might be construed as an economic decision. In the case of motivational conflict — consideration of an option that has both associated costs and benefits (e.g., money and saltwater) — appetitive motivation can be used to increase the subjective value of an option, thus offsetting the cost of engaging cognitive control (which would otherwise have negative subjective value; top panel). By contrast, aversive motivation has the opposite influence, decreasing the value of an otherwise attractive option (i.e., with positive appetitive value), and reducing cognitive control engagement via motivational conflict (bottom panel).

behavior (i.e., better performance on juice + money trials, poorer performance on saltwater + money trials compared with tasteless liquid + money; Figure 3b). As the foregoing suggests, motivational valence is an important dimension that should be more systematically explored in future investigations of motivation–cognition interactions, as it may lead to deeper insights regarding more complex issues, such as incentive integration (i.e., bundling) and motivational conflict [67–69].

Conclusions

Recent studies of motivation–cognitions have primarily focused on understanding whether, how, and why motivation interacts with cognitive control. The recent VBCC framework conceptualizes the motivation–cognition interaction as a decision-making process that juxtaposes motivation and cognitive effort costs. We suggest promising future directions regarding how to incorporate Pavlovian versus instrumental influences and motivational valence/conflict into this research domain. It is our hope that this review spurs future innovative investigations, which could also extend into broader relevant issues such as aging and developmental trajectories [70–72], and the neural mechanisms of psychopathology [73].

Conflict of interest statement

Nothing declared.

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- •• of outstanding interest

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