Cognitive Control in the Service of Self-Regulation

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Glossary

Cognitive control – The organization of thoughts, behaviors, and emotions to achieve selected goals.
Conflict – The cognitive state that arises from competition between different behavioral options when only one option may be selected.
Dorsolateral prefrontal cortex – An area of the prefrontal cortex that comprises Brodmann's areas 9 and 46 and that subserves working memory and top-down attention.
Response inhibition – Inhibition of behavioral responses that are goal or task irrelevant.
Self-regulation – It encompasses cognitive control as well as the selection of goals and their interactions with current and learned parental, social, and cultural influences.
Striatum – The major input structure of the basal ganglia, consisting of the caudate nucleus and putamen. Portions of the striatum are important for the encoding of well-learned motor and cognitive tasks.
Stroop Task – Cognitive task in which each trial consists of a colored word. In congruent trials, the ink color is the same as the color that the word denotes. In incongruent trials, the ink color differs from the color that the word denotes. The subject's task is to name the ink color. The conflict inherent in incongruent trials causes participants to take longer to respond and make more errors on those trials than on congruent ones.
Top-down attention – Goal-driven selection of task-relevant stimuli or features that may not be the most salient and might, therefore, not be attended otherwise.
Ventrolateral prefrontal cortex – An area of the prefrontal cortex that comprises Brodmann's area 47 and that is important for response inhibition.

Introduction

Conflict arises from competition between different behavioral options when only one may be selected. Conflict is ubiquitous in everyday life, in that we are constantly pulled in multiple directions. On a given day, we may need to accomplish a task that others are depending on us to complete while we are simultaneously tempted by more pleasing activities. We may have to finish a review for an employer or pay the bills when a friend calls with an invitation to watch a sporting event. Even choosing not to act may produce conflict, since it involves an assessment of the risks and benefits of not undertaking possible actions.

Appropriate resolution of conflict occurs when the choice among competing behavioral options offers the greatest overall benefit to the individual. Often, this requires the inhibition of automatic or immediately rewarding options in favor of nonautomatic, effortful options that are better aligned with the organism's long-range goals. This requires cognitive control – the goal-oriented organization of thoughts, behaviors, and emotions.

The concept of cognitive control poses the difficult questions of who is doing the controlling and why? Who is controlling the controller? These questions raise the age-old paradox of the homunculus pulling at the strings of thought and action. The paradox boils down to the problem of the origins of goal selection. Why do we choose to pursue certain goals rather than others? These choices are the products of the complex influences and interactions of individual, familial, societal, and cultural values, reinforcements, and other determinants. Cognitive control, in contrast, refers to the mechanisms supporting the coordination of thought and action to achieve given goals; the origin of the goals themselves is beyond the scope of cognitive control.

The term 'cognitive control' comes from cognitive psychology and cognitive neuroscience; a related term that is used in these and a variety of other disciplines is 'self-regulation'. The latter term is, sometimes, used with slightly different meanings across disciplines. For our purposes, the concept of self-regulation is related to, but broader than, that of cognitive control. Whereas cognitive control refers to a set of cognitive mechanisms that allow action to be aligned with internal goals, the concept of self-regulation also includes the origin of those goals and their interaction with current and learned parental, social, and cultural influences. Self-regulation often engages cognitive control mechanisms to achieve goals, but it also includes the broader context and choice of those goals. For example, self-regulation may include a set of internalized moral imperatives according to which an individual seeks to behave, and it may establish goals consistent with those moral imperatives. Cognitive control can then be engaged to achieve those goals (e.g., a person may inhibit the impulse to buy an expensive material object so as to use the money instead to help a friend in need).

Self-regulation and cognitive control play a central role in normal mental and behavioral functioning, and its impairment is a central sign in many neuropsychiatric and behavioral disorders. We can consider the example of people who suffer from bipolar disorder (BD), who have great difficulty inhibiting their responses to behavioral options that offer immediate rewards, such as sex or spending sprees. At the same time, they may neglect longer-term goals that would produce more rewarding long-term gains, while they simultaneously incur many painful consequences of their impulsive behavior.

Attention in the Service of Cognitive Control

Attention allows an individual to resolve conflict by selecting task-relevant information and ignoring task-irrelevant information. This is best illustrated by a classic example from experimental psychology, the Stroop interference effect, named after its discoverer. Participants are asked to identify the ink color in which words are written. Conflict arises because the words also spell names of colors, which may or may not be the same as the ink color. Each trial consists of a single colored word. In congruent trials, the ink color is the same as the color that the word denotes. In incongruent (conflict) trials, the ink color differs from the color that the written word denotes. Participants take longer to respond and they make more errors on incongruent trials than on congruent ones. This is one of the most robust and best-replicated findings in all of behavioral neuroscience.

Responding in incongruent trials is slow and prone to error because reading is a highly practiced, automatic task, whereas color naming is not. To name the ink color rather than read the word, participants must, therefore, inhibit the more automatic task in order to correctly perform the less automatic one. This requires the allocation of attentional resources and the resolution of the two competing behavioral tendencies, the naming of colors and word reading. Resolving these two tendencies requires more time to complete the task. Failure to boost activity appropriately in the neural pathways associated with color naming or to suppress activity in the neural pathways associated with word reading produces error, which nearly always is responding with the color that the conflicting word denotes. In contrast, when the ink color is the same as the color that the word denotes, the response tendencies for the two tasks are identical, and the task is much easier and less prone to error. In fact, the presence of a congruent word speeds the naming of the ink color, compared to the naming of the ink color of, for example, a colored patch.

One model of the Stroop task helps to explain how the human uses attention to boost activity in task-relevant neural pathways when faced with competing activation in task-irrelevant pathways. Several versions of this model have been developed over the years, but the basic mechanisms underlying all of them are similar. A typical version of the model is depicted in Figure 1. It includes a sensory input layer, an association layer, and a response layer – all of which are connected via feedforward connections. Separate units in the input layer represent the written text and the ink's color of a colored word. These

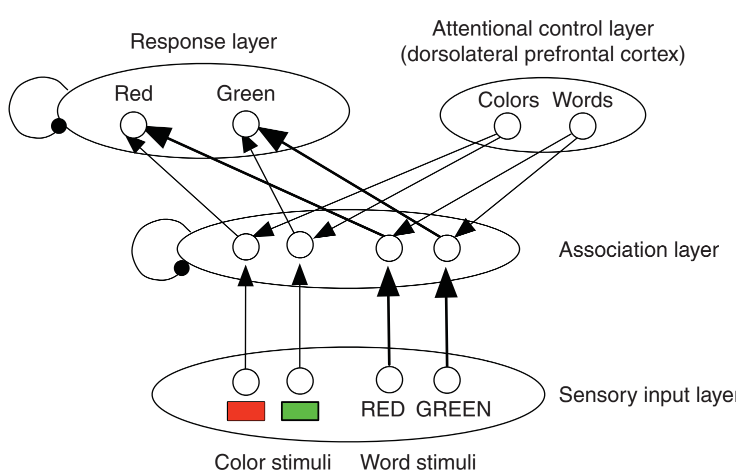

Figure 1 Connectionist model of the Stroop task. The model consists of three layers – sensory input, association, and response layers – that communicate through feedforward connections. Additionally, an attentional control layer provides top-down control to bias either the word-reading or the color-naming pathways. Layers are indicated by ovals; processing units within layers are indicated by circles. Connections between units are indicated by arrows. The width of the arrows represents the strength of the connections.

units project to corresponding units in the association layer, where lateral inhibition introduces competition between the units. Further competition occurs at the response level via lateral inhibition between the units that represent the possible responses. An attentional control layer, representing the dorsolateral prefrontal cortex (DLPFC), projects to the association layer. The role of the attentional control layer is to bias activation in the association layer in a task-relevant way. Such biases are often called 'top-down' influences on activity in the association layer, reflecting the common notion that the brain is organized hierarchically, with the DLPFC at the top of the hierarchy controlling activity in areas lower in the hierarchy, such as the posterior cortex and subcortex. We note that the validity of this hierarchical view of the brain is not essential to the validity of the connectionist model. All that is essential to the latter is the capacity to flexibly, but selectively, alter the strength of activity in one pathway compared with activity in another pathway according to task demands.

The strength of connections from one layer to another, indicated by the width of the arrows in Figure 1, reflects the degree of automaticity of the competing behavioral tendencies of word reading and color naming. Thus, connections are stronger for the word-reading than for the color-naming pathway. Incongruent stimuli will, therefore, activate the units in the word-reading pathway more strongly and, without top-down attentional control, will produce a response that denotes the written word. The attentional control layer, however, contains units that can provide top–down activation that can differentially boost activity in either the color-naming or the word-reading pathway. Appropriately activating the 'colors' unit in the attentional control layer increases responsivity of the color-naming pathway to support color naming, even for incongruent stimuli. Nevertheless, color naming is slower and more prone to errors when responding to incongruent than to congruent stimuli, because incongruent words interfere with the processing and naming of colors via the competitive dynamics present in the association and response layers.

A key question not addressed by the model is how the instructions to name the colors or read the words are translated into appropriate activations in the attentional control layer. This question is even more complicated if one generalizes the model to address the allocation of attention that is required to pursue dynamically changing goals as encountered in everyday life. How are goals translated into the appropriate patterns of activation in the attentional control layer? How are the appropriate connections from that layer to the associative layer formed?

Unfortunately, the model is not yet designed to address fully questions that extend beyond cognitive control and into the broader domain of self-regulation. To perform appropriately in the Stroop task, for example, participants must have the goal of complying with the task instructions. But what is the origin of that goal? It likely is a product of complex interactions among the participant's understanding of the desirability of certain types of behavior in given social or academic situations, the desire to perform well, or the motivation provided by external rewards, if available. While these processes of goal selection are taken for granted in most experimental situations, their influence is likely to be even greater, and their interactions more complex in real life. Undoubtedly, the appropriate allocation of attention or inhibition of task-irrelevant responses requires clear goals. In experimental settings, these goals often are clearly defined by the experimenter (but assuming that the participant wants to comply with task instructions). However, in real life, goals themselves are dynamic and often underdetermined. A key component of self-regulation is the ability to select goals consistent with one's values. Future research on self-regulation should emphasize the process of goal selection, the relation between goals and learned values, and the origin of values themselves.

The degree to which a given task is automatic or requires effort is not fixed but, instead, can be changed by practice. The effects of practice and prior experience on the degree of automaticity of behavioral tendencies may reflect the strengthening of synapses from the input layer to the association layer, and from the association layer to the response layer for the relevant task. As the pathway corresponding to a given behavioral tendency is strengthened, execution of tasks that engage that behavior relies less on top-down control by the DLPFC. Evidence for this claim comes from the finding that activation of the DLPFC decreases with additional training in given tasks.

The prefrontal cortex and basal ganglia are intimately interconnected in cortico-striato-thamalo-cortical (CSTC) loops. At least five such loops have been identified, each involving projections to and from different cortical areas. With extensive training, activity during performance of motor-planning tasks shifts from the CSTC loop that involves the DLPFC to the CSTC loop that involves sensory and motor cortices. Behavioral tendencies that are more controlled and effortful on the one extreme, therefore, lie along a continuum with more automatic behavioral tendencies on the other extreme, with the degree of control and automaticity changing along this continuum as a consequence of prior experience and practice.

Neural Monitoring of Conflict

Discerning the nature of conflicting behavioral tendencies and detecting when they occur is essential to the appropriate resolution of conflict. Conflict can occur when the processing of two or more stimuli competes or when a response must be selected from among two or more competing behavioral responses. Considerable experimental evidence suggests that the ACC (Brodmann's Area 24) is the neural locus for detecting conflict both at the level of stimulus processing and at the level of response.

The ACC can help to resolve detected conflict only if it signals the presence of the conflict to a neural system, such as the DLPFC, that can then appropriately deploy the attentional resources and control required to resolve the conflict that accompanies the simultaneous presence of conflicting stimulus processing or response tendencies, as occurs in the Stroop effect. The ACC and DLPFC, therefore, cooperate by detecting conflict within the ACC and then deploying the cognitive control systems within the DLPFC that are required for correct, goal-directed responding.

The ACC also seems to participate in detecting the occurrence of errors in responding. Studies using event-related potentials (ERPs), for example, have established firmly that the so-called 'Error Related Negativity,' a peak deflection over the ACC, occurs approximately 100 ms following an erroneous response. Multiple functional magnetic resonance imaging (fMRI) studies also report activity in the ACC following errors. These findings are consistent with those from studies using single-unit recordings in monkeys, which show that increases in activity of ACC neurons signal error when monkeys fail to inhibit a planned, task-guided saccade. The seemingly different conflict-detecting and error-detecting activities of the ACC can potentially be reconciled by considering the detection of errors as a form of conflict, one in which a person recognizes that the actual, erroneous response differs from (and, therefore, conflicts with) the correct response.

Similar to conflict in the Stroop task, which we might designate 'cognitive conflict,' 'emotional conflict' arises when an emotionally salient stimulus competes with task demands. Conflict in the classical color-naming Stroop task activates the dorsal division of the ACC. In the emotional Stroop task – in which conflict is produced by the presentation of words with emotional valence (e.g., 'murder') – conflict, instead, activates the ventral, or affective, division of the ACC. The dorsal and ventral ACC exhibit opposite patterns of activation, with the ventral ACC decreasing and the dorsal ACC increasing activity during cognitive conflict, whereas the dorsal ACC decreases and the ventral ACC increases activity during emotional conflict.

Neural Mechanisms of Control

The DLPFC uses top-down attention to enhance processing along task-relevant neural pathways. Top-down attentional processes should be distinguished from bottom-up ones. Bottom-up attention is a consequence of the salience of stimulus features (e.g., loud noises) that automatically attract attention. Top-down attention, in contrast, involves the goal-driven selection of task-relevant stimuli or features that may not be the most salient and, thus, would not necessarily be attended using only the bottom-up mechanism. In the connectionist model of the Stroop Task, bottom-up processing is reflected in the strength of connections between the input, association, and response layers. Top-down processing is modeled by the top-down influences of the attentional control layer onto the association layer. In the Stroop task, when naming colors, participants use top-down processing to attend to colors and to override the bottom-up tendency to attend to and read words.

Top-down attention functions similarly irrespective of whether salience is determined by static stimulus features or by the frequency of stimulus presentation. Stimuli that are presented in an unpredictable, oddball fashion have greater salience and are thus more prone to capture attention. If such oddball stimuli are behaviorally irrelevant, greater top-down attentional control must be used to inhibit their processing.

The top-down attentional control exercised by the DLPFC is flexible and can change in the context of changing task goals, task demands, or motivational states. This contrasts with a habit-learning system that is based within the dorsal striatum and that guides action selection via previously learned stimulus–response (S–R) associations. One theory suggests that the prefrontal and dorsal striatal systems balance their control over behavior according to Bayesian principles, such that each system guides behavior when it is likely to be the most accurate of the two (i.e., when the uncertainty associated with its predictions is smaller than that associated with the other system's predictions).

Response Inhibition

In addition to the deployment of attention for selective stimulus processing, cognitive control depends on the inhibition of goal- or task-irrelevant responses. Appropriate development of response inhibition is also critically important for normal development, and impaired maturation of this cognitive ability may produce or predispose to disorders of impulse control. The prefrontal cortex is fundamental for response inhibition, just as it is for attention, consistent with the idea that the prefrontal cortex exerts top-down control over other brain regions and circuits. Top-down control is precisely the type of mechanism necessary to inhibit prepotent responses and responses that have already been initiated. The specific portions of the prefrontal cortex that are involved in response inhibition differ, however, from those that have been implicated in attentional facilitation. Whereas attention relies largely on the DLPFC (and related, interconnected portions of parietal cortex), response inhibition appears to rely instead on the ventrolateral prefrontal cortex (VLPFC). Different areas of prefrontal cortex seem, therefore, to be specialized for different cognitive control functions.

Response inhibition is often studied using the Go/No-Go task. The participant must perform an action, such as pressing a button, when a given stimulus is presented ('Go' trials), and refrain from performing the action when a different stimulus is presented ('No-Go' trials). If Go trials are much more frequent than No-Go trials, the participant has difficulty inhibiting the response on No-Go trials, producing a higher error rate on the No-Go trials.

Another task commonly used to study response inhibition is the Stop-Signal Reaction Time (SSRT) task. In this task, participants perform a speeded response to a stimulus. On some trials, however, that stimulus is followed after a brief delay by a stop signal indicating that the response should not be performed. This task permits estimation of the SSRT, a measure of the time required to suppress a response. The greater this measure, the greater the difficulty in inhibiting a behavioral response. Many functional imaging studies show activation of the VLPFC in Go/No-Go and SSRT tasks, and lesion studies have shown that the extent of damage in the right VLPFC correlates with the SSRT, providing direct evidence for a causal role of the VLPFC in inhibiting the behavioral response during the SSRT task. Damage in other areas of the prefrontal cortex does not correlate with the SSRT, suggesting that response inhibition may depend primarily on VLPFC and not on other areas of prefrontal cortex. The prefrontal cortex and basal ganglia, moreover, seem to subserve distinct aspects of response selection and inhibition, with the striatum subserving the lower-order translation of stimuli to behavioral responses and the VLPFC and DLPFC subserving adaptation to changing task rules. Finally, backward-masking procedures used in conjunction with electrophysiological recordings have shown that inhibitory cues can be processed similarly with or without conscious awareness, and therefore the 'higher' cognitive process of behavioral inhibition can be influenced by stimuli that are outside of awareness.

Response inhibition seems to mature to a greater degree (i.e., it changes over a larger range of values) than does selective attention from childhood to adulthood. Performance differences on a Go/No-Go task are greater than performance differences on tasks of attentional control when measures of performance in young children are compared with performance measures on the same tasks in adults. Moreover, the difference in frontostriatal blood-oxygenation-level-dependent (BOLD) activation between young children and adults is greater for tasks requiring response inhibition than for tasks requiring selective attention. The development of response inhibition may, therefore, be even more important than that of selective attention for behavioral control and the successful transition from childhood and adolescence into adulthood.

Impaired Control and Psychopathology

Impairments in attention or inhibitory control have been implicated in a wide variety of disorders, including attention-deficit/hyperactivity disorder, anorexia nervosa, bulimia nervosa, obsessive-compulsive disorder, and schizophrenia. In this article, we focus on the evidence for impaired cognitive control in BD as an example of the relevance of control to the understanding of psychopathological processes. A similar approach has been used for several other disorders.

BD is a chronic, but treatable, disorder of affect, thought, and behavior that produces long-term interpersonal and functional disability. *The Diagnostic and Statistical Manual*, Version IV (DSM-IV) defines BD by the history of at least one manic episode, defined as elevated mood and energy that lasts for at least a 2-week period. In addition, patients with BD often have periods of depression, with low mood, low energy, and loss of interest in people and activities that were previously enjoyable. Sufferers of BD have difficulty controlling their behaviors, thoughts, and emotions. They engage in impulsive behavior (e.g., spending sprees); they often have racing thoughts when in a manic state and difficulty controlling ruminations about negative experiences when in a depressed state; and they are emotionally labile, unable to control their emotions, which can change quickly over a large range, from profound sadness to excited elation. These symptoms suggest an impaired ability to exercise cognitive control of behaviors and thoughts as traditionally defined, as well as difficulty with the cognitive control of emotion, which sometimes is termed 'emotional regulation.'

Consistent with a putative deficit in cognitive control, patients with BD exhibit anatomical and functional abnormalities in brain regions and circuits that subserve cognitive control, including the ACC, DLPFC, and VLPFC. Persons with BD, for example, have reduced ACC and DLPFC activity compared with healthy controls while performing the Stroop task. Activity of the VLPFC is also lower in patients with BD who are in the euthymic state as they make erroneous, impulsive responses on the Go/No-Go task, suggesting that a trait deficit in top–down prefrontal control may underlie a behavioral tendency toward impulsivity in these people.

In addition to these deficits in cognitive control as traditionally defined, persons with BD are also reported to have anatomical and functional abnormalities in brain regions such as the orbitofrontal cortex and the ventral portion of the medial wall, that have been implicated in emotional regulation. In addition, prefrontal control of affective state seems to be impaired in persons with BD, reflected in hypoactivation of the subgenual prefrontal cortex (Brodman's Area 25), during depressive episodes. The abnormalities in prefrontal BOLD activation seen during depressed and manic episodes are generally hemisphere- and state-specific, with left prefrontal reductions reported during depressive states and right prefrontal reductions reported during mania.

Conclusion

The constructs of self-regulation and cognitive control that we have reviewed are useful in understanding both normal function and psychopathological processes. We have outlined self-regulation at several levels. First, we illustrated the differences between behaviors that are automatic and those that require effortful control. Second, we defined the central concept of conflict as it relates to the need for self-regulation and control, and we reviewed how the brain is thought to detect conflict and resolve it by appropriately deploying cognitive control. Third, we reviewed the role of response inhibition in the control of behavior. Finally, we have exemplified the usefulness of these concepts to understanding psychopathological processes through discussion of what are believed to be core deficits in self-regulatory control in persons with BD.

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See also: Animal Models of Bipolar Disorder; Attention and Speed of Information Processing; Brain Imaging; Cognition: Attention and Impulsivity; Emotion–Cognition Interactions; Evolutionary and Developmental Issues in Cognitive Neuroscience; Motivation; Neural Basis of Attention-Deficit/Hyperactivity Disorder.

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