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Executive Function

The Search for an Integrated Account

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ABSTRACT—*In general, executive function can be thought of as the set of abilities required to effortfully guide behavior toward a goal, especially in nonroutine situations. Psychologists are interested in expanding the understanding of executive function because it is thought to be a key process in intelligent behavior, it is compromised in a variety of psychiatric and neurological disorders, it varies across the life span, and it affects performance in complicated environments, such as the cockpits of advanced aircraft. This article provides a brief introduction to the concept of executive function and discusses how it is assessed and the conditions under which it is compromised. A short overview of the diverse theoretical viewpoints regarding its psychological and biological underpinnings is also provided. The article concludes with a consideration of how a multilevel approach may provide a more integrated account of executive function than has been previously available.*

KEYWORDS—*executive function; frontal lobe; prefrontal cortex; inhibition; task switching; working memory; attention; top-down control*

Like other psychological constructs, such as memory, executive function is multidimensional. As such, there exists a variety of models that provide varying viewpoints as to its basic component processes. Nonetheless, common across most of them is the idea that executive function is a process used to effortfully guide behavior toward a goal, especially in nonroutine situations. Various functions or abilities are thought to fall under the rubric of executive function. These include prioritizing and sequencing behavior, inhibiting familiar or stereotyped behaviors, creating and maintaining an idea of what task or information is most relevant for current purposes (often referred to as an attentional or mental set), providing resistance to information that is distracting or task irrelevant, switching between task goals, utilizing relevant information in support of decision making, categorizing or otherwise abstracting common elements across items, and handling novel information or situations. As can be seen from this list, the functions that fall under the category of executive function are indeed wide ranging.

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ASSESSING EXECUTIVE FUNCTION

The very nature of executive function makes it difficult to measure in the clinic or the laboratory; it involves an *individual* guiding his or her behavior, especially in novel, unstructured, and nonroutine situations that require some degree of judgment. In contrast, standard testing situations are structured—participants are explicitly told what the task is, given rules for performing the task, and provided with information on task constraints (e.g., time limits). Since executive function covers a wide domain of skills, there is no single agreed-upon “gold standard” test of executive function. Rather, different tasks are typically used to assess its different facets.

One classic test often used to assess the compromise of executive function after brain injury is the Wisconsin Card Sorting Test. This task is thought to measure a variety of executive subprocesses, including the ability to infer the categories that should guide behavior, the ability to create an attentional set based on those abstract categories, and the ability to switch one’s attentional set as task demands change. Briefly, individuals must deduce from the experimenter’s response the rule by which the cards should be sorted (rather than being told the rule explicitly; see Fig. 1a). After the initial rule is learned successfully, the examiner changes the rule without informing the individual. At this point the old rule must be rejected, the new rule discovered, and a switch made from the old rule to the new. The ability to exhibit such flexible readjustment of behavior is a cardinal characteristic of executive function. Individuals with frontal lobe damage and children younger than 4 years (who are typically tested on a two-dimensional version of the sorting task) tend to persist in sorting items according to the previous and now inappropriate rule.

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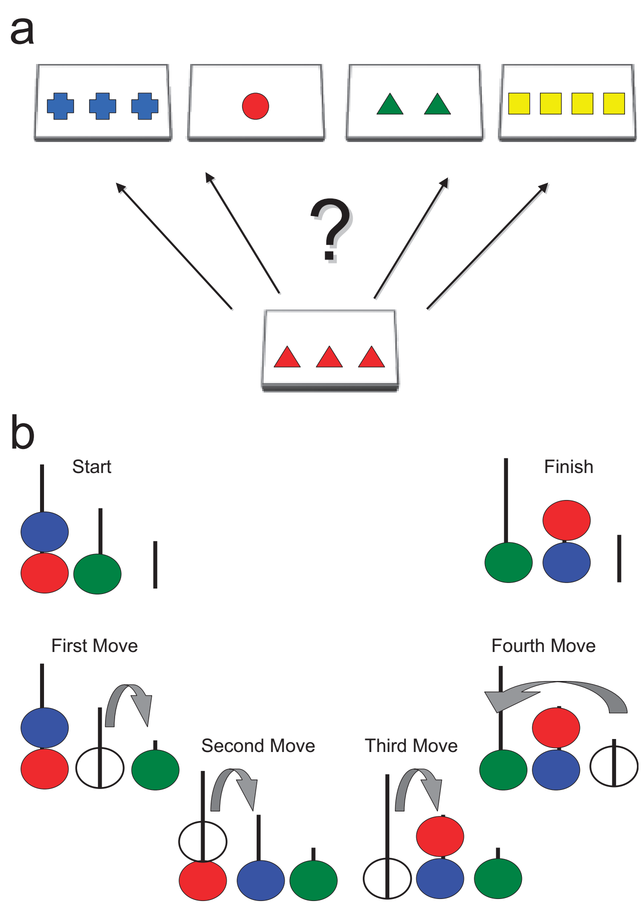

Fig. 1. Examples of tasks often used to assess executive function. In the Wisconsin Card Sorting Test (a), individuals must sort cards into one of four piles; each card has items on it that vary along three dimensions—color, number, and shape—with each dimension having one of four values (e.g., Color: red, blue, green, or yellow; Number: 1, 2, 3, or 4; Shape: circle, square, triangle, or cross). Individuals must deduce the correct rule (i.e., dimension) on which to sort the cards based on feedback provided by the examiner about whether each choice made was correct or incorrect. When the rule is changed, individuals with prefrontal damage and children younger than 4 often perseverate on this type of task. They are either unable to learn the new rule or return to the old rule even after they have successfully sorted a number of trials by that new rule. In the Tower of London task (b), an individual is shown a series of items with an initial state and a goal state; on every trial, there are three pegs, which can hold one, two, and three balls, respectively. The individual must determine the shortest number of moves required to get from the initial state to the final goal state. In some cases, such as in the sequence shown here, the individual may have to backtrack—that is, move a ball to a temporary position (the first move) before moving it back to its final position.

Cognitive psychologists have attempted to disentangle the different executive subprocesses that underlie performance on the Wisconsin Card Sorting Test, as well as to identify other executive subprocesses. For example, the ability to switch mental sets has been studied by presenting individuals with multidimensional stimuli (e.g., a colored numeral) along with a cue that indicates the attribute on which a response should be based (e.g., color, or whether the number is odd or even). Individuals are slower to respond and make more errors on trials requiring a task switch (e.g., categorize by color preceded by categorize by odd/even) than they do on those that do not (e.g., categorize by color preceded by categorize by color), indicating that task switching requires executive control (Monsell, 2003).

In other executive tasks, decisions must be based on task-relevant information in the face of distracting information. One such measure of this ability is the Stroop task, in which a word's color must be identified while ignoring the word itself. Since word reading is more automatic than color naming, executive control is required to override the tendency to read or to respond on the basis of the word rather than the ink color. The need for such control is reflected in slower responses when the word names a competing ink color (e.g., the word "red" printed in blue ink) than when it does not (e.g., the word "sum" in red ink or the word "red" in red ink).

Other tasks, such as the Tower of London task, examine the ability to plan and sequence behavior towards a goal. In this task, a start state and a goal state are shown, and the individual must determine the shortest number of moves required to get the balls from the starting state to the goal state (see Fig. 1b). An inability to solve the problems, taking more steps than necessary, and/or impulsively starting to move the balls before planning are all symptoms of executive dysfunction on this task.

THE COMPROMISE OF EXECUTIVE FUNCTION

Psychologists are interested in executive function because it is critical for self-directed behavior, so much so that the greater the decrement in executive function after brain damage, the poorer the ability to live independently (Hanks, Rapport, Millis, & Deshpande, 1999). Normal children, adolescents, and older adults also show decrements in executive function. Most notable in children is their perseveration when required to switch tasks. Although they can correctly answer questions about what they *should* do, they nonetheless are often unable to produce the correct motor response (Zelazo, Fyre, & Rapus, 1996). Similarly, parents often wonder why teenagers take risks and make imprudent decisions even though they seem to "know" better. This demonstrated knowledge about abstract rules coupled with an inability to implement them, especially in the face of distracting or conflicting information, is reminiscent of that observed in children. The ability to plan ahead in multistep processes, to learn about contingences between reward and punishment in multifaceted decision-making tasks, and to exert inhibitory control and reduce impulsive behavior continues to increase during the teenage years and, in fact, well into the early 20s (Steinberg, 2007). Executive function is also the cognitive ability most affected by aging (e.g., Treitz, Heyder, & Daum, 2007), with even more severe decline associated with mild cognitive impairment and Alzheimer's disease. Finally, executive function is compromised across a large number of psychiatric illnesses, including schizophrenia, bipolar disorder, depression, substance use disorders, and attention deficit hyperactivity disorder (e.g., Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

PSYCHOLOGICAL AND NEUROBIOLOGICAL MODELS OF EXECUTIVE FUNCTION

Even though there is agreement that damage to the frontal lobe is associated with compromised executive function, there is little accord on much else—with regard either to the cognitive components of executive function or to the manner in which the frontal lobe supports executive function. This lack of consensus seriously inhibits our understanding of the psychological and neural mechanisms underlying executive function, as well as the development of treatments to prevent or ameliorate deficits in this area.

To somewhat oversimplify a complicated literature, one class of models argues that executive function is an emergent function of a more basic, largely monolithic psychological construct like general intelligence (*g*), fluid intelligence, reasoning and processing speed, or the ability to actively maintain information online to meet task demands (often conceptualized as working memory; e.g., Salthouse & Davis, 2006). Studies examining individual differences in task performance across neurologically intact individuals suggest that there may actually be distinct subcomponents to executive function, including the ability to inhibit a prepotent response, the ability to shift the task set guiding behavior, and the ability to update the contents of working memory. Of note, studies of twins suggest that at least some of these subcomponents, notably response inhibition and set shifting, appear to be separable from *g* (Friedman et al., 2006).

Equally contentious are theories regarding the neural mechanisms of executive function. Some researchers have argued that lateral regions of the prefrontal cortex (PFC) are engaged across a diverse set of demands that engage executive function (Duncan & Owen, 2000). Such theories are consistent with findings that the performance of patients with frontal lobe lesions across distinct tasks can be explained by a single factor. Other theories hold, however, that distinct regions of the prefrontal cortex are involved in different aspects of executive functions. For example, Petrides (2005) has argued that inferior lateral regions of the prefrontal cortex (Brodmann Areas [BA] 45, 47) maintain information in working memory while others, notably mid-dorsolateral prefrontal regions (BA 9, 46), perform executive-control operations on that information. Another theory is that control mechanisms in the prefrontal cortex are organized in a hierarchical manner, with more anterior regions using internally generated information to guide behavior and more posterior regions using information from the environment (Christoff & Gabrieli, 2000). Another idea, based on the pattern of decrement found across a battery of tests in patients with focal frontal lesions, is that there are three main types of executive function, each associated with a different part of the frontal cortex. In this view, initiating and sustaining a response rely on medial frontal regions, task setting relies on left lateral regions, and monitoring involved in checking and adjusting task performance over time relies on right lateral regions (Stuss & Alexander, 2007).

Based on functional neuroimaging studies with the Stroop task, our laboratory has taken yet another view. We suggest that executive function involves a temporal cascade of selection processes that are implemented at distinct way stations in the PFC (see Fig. 2). In this model, posterior regions of the dorsolateral PFC (DLPFC) impose an attentional set toward task-relevant processes. This region activates when it is difficult to ignore information that engages a task-irrelevant process, regardless of the type of task-irrelevant process (e.g., word reading, color identification) or the nature of the process that is required for the task (e.g., color identification, object identification; Banich et al., 2000). In contrast, the mid-DLPFC selects among the specific representations identified as task-relevant. For example, this region becomes activated for both incongruent (e.g., "red" in blue ink) and congruent (e.g., "red" in red ink) trials in the Stroop task, because one must determine which source of color information (that contained in the ink color or that contained in the word) is task-relevant (Milham, Banich, & Barad, 2003). Posterior portions of the dorsal anterior cingulate cortex (ACC) tend to be involved in late-stage aspects of selection, being especially sensitive to response-related factors. This region shows the greatest activity when stimuli lead to two competing responses and is less sensitive to semantic types of conflict (Milham et al., 2001). Finally, anterior regions of the dorsal ACC appear to be involved in processes related to response evaluation, as activity in this region increases when the probability of making an error increases (Miham & Banich, 2005). An important part of our theory is that how much any of these executive-control mechanisms are invoked depends on how effectively control was applied at earlier way stations, with activity in the ACC being affected by how well regions of DLPFC impose control. For example, with increased practice at a Stroop task, activity in the DLPFC drops slightly, but that of the posterior dorsal ACC diminishes greatly as control by DLPFC becomes more effective (Milham, Banich, Claus, & Cohen, 2003). Conversely, relative to younger adults, older adults show less DLPFC activity but increased cingulate activity (Miham et al., 2002), which is consistent with the cascade-of-control model.

TOWARD AN INTEGRATED MODEL

How can all these different conceptions of executive function be reconciled? This is a major challenge facing the field today. In pursuit of a more integrated account of executive function, our laboratory is working collaboratively along with others at the University of Colorado and the University of Illinois under the auspices of a National Institute of Mental Health center grant to

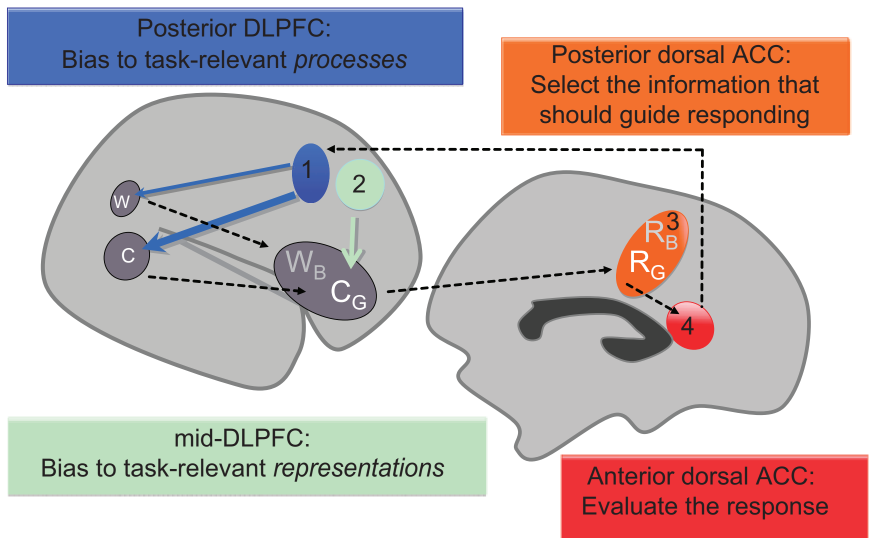

Fig. 2. The cascade-of-control model of executive function in frontal cortex. Here we show how the cascade-of-control model (Banich et al., 2000; Milham & Banich, 2005; Milham, Banich, Claus, & Cohen, 2003; Milham et al., 2002) would explain performance on the Stroop task. The example shown is for the word ''blue'' printed in green ink. The direction of the cascade is indicated by the dashed arrows. First, posterior regions of the dorsolateral prefrontal cortex (DLPFC; 1) create and impose a top-down attentional set for task-relevant goals. In this case, a top-down attentional set is imposed toward activation of brain regions involved in ink-color identification (C). This bias must be strong (as denoted by the thick line) to counteract the automatic bias (noted by a thin line) toward brain regions that are involved in word processing (W). However, this top-down attentional set cannot overcome a lifetime of word reading, so selection must occur among the representations that are identified as related to color. We argue that mid-DLPFC (2) selects which of the representations, most likely being actively maintained, is most task relevant. Here the selection would be toward the ink color green (C_G) as compared to the word ''blue'' (W_B). Next, posterior regions of the dorsal anterior cingulate cortex (3) must determine what information should be used in determining the response (R), in this case selecting the response (either verbal or manual) associated with green (R_G) as compared to the response associated with blue (R_B). However, if selection by prior regions in the cascade (i.e., those in DLPFC) is poor, the posterior dorsal cingulate must also deal with any unresolved issues of selection from prior way stations in the cascade before a response can be emitted. Finally, more anterior regions of the dorsal anterior cingulate cortex (ACC; 4) are involved in response evaluation. If such an evaluation suggests that an incorrect response was made, these anterior regions of the dorsal ACC send a signal back to posterior-DLPFC, telling it to assert top-down control more strongly.

link theories of executive function across different levels of analysis. We are considering the nature of executive function at three distinct levels: the neurobiological (at the level of both neurotransmitters and brain systems), the psychological, and the computational. Our goal is to consider how information at each of these levels can be linked, and thereby lead to a theory of executive function that can better account for the many disparate pieces of knowledge currently available.

One example of an issue being actively examined within our center is the nature of executive processes involved in the imposition and switching of task sets. Our computational models, as well as empirical studies of neurotransmitter function, suggest that dopaminergic connections from the basal ganglia to the frontal cortex act as a gate, signaling whether one should hold onto the information currently being maintained in working memory or clear it out to allow new information to enter (O'Reilly, 2006). These findings raise the possibility that genetic variation in dopaminergic function influences the maintenance and switching of task sets, a possibility we are currently investigating. At the level of brain systems, one major area affected by this gating would be the posterior portion of the DLPFC, which according to our cascade-of-control model is involved in creating and maintaining an attentional set. Moreover, recent work by colleagues at the University of Illinois suggests that these same posterior regions of the DLPFC are involved in creating and maintaining an "affective" set, as activity in this region during attentionally demanding tasks differs between depressed and nondepressed individuals (Herrington et al., 2009). Developmental research in our center shows, at the psychological and computational levels, that a child's ability to create abstract representations of categories predicts her or his task-switching abilities (Kharitonova, Chien, Colunga, & Munakata, in press). One potential explanation is that actively maintained task-set representations are relatively weak in children. They only become stronger, as well as more abstract and able to be generalized, with practice or experience. Hence, a new task set with which a child lacks experience will be relatively weak compared to a prior task set that has been used repeatedly on preceding trials.

These are some of our first steps at linking neurobiological, psychological, and computational approaches in an effort to better understand executive function. How might such an integrated account be helpful? We believe that a more integrated account may aid in the design of new interventions for executive dysfunction. For example, our findings suggest the possibility that training people in building abstract categories may bolster aspects of executive function such as task switching. One difficulty with training regimens is that sometimes their results are not immediately apparent but are only seen down the road. Brain imaging might provide a means to determine whether additional or different regions come on line during the course of training even before behavioral changes are manifest. Studies with drug interventions might provide another way to bolster engagement of brain regions necessary for executive function. In sum, an integrated understanding of executive function should open up new avenues for intervention to aid individuals who have compromised executive functioning because of a psychiatric disorder, brain damage, aging, or other factors.

Recommended Reading

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Royall, D.R., Lauterbach, E.C., Cummings, J.L., Reeve, A., Rummans, T.A., Kaufer, D.I., et al. (2002). Executive control function: A review of its promise and challenges for clinical research. A report from the Committee on Research of the American Neuropsychiatric Association. *Journal of Neuropsychiatry & Clinical Neurosciences*, *14*, 377–405. Discusses the psychiatric and medical disorders that are associated with compromised executive function, how executive function is assessed in clinical settings, and the linkage of executive function with functional outcome; also discusses challenges in designing treatments for executive dysfunction.

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