The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions

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Abstract

Executive functions (EFs)—a set of general-purpose control processes that regulate one's thoughts and behaviors—have become a popular research topic lately and have been studied in many subdisciplines of psychological science. This article summarizes the EF research that our group has conducted to understand the nature of individual differences in EFs and their cognitive and biological underpinnings. In the context of a new theoretical framework that we have been developing (the unity/diversity framework), we describe four general conclusions that have emerged. Specifically, we argue that individual differences in EFs, as measured with simple laboratory tasks, (a) show both unity and diversity (different EFs are correlated yet separable), (b) reflect substantial genetic contributions, (c) are related to various clinically and societally important phenomena, and (d) show some developmental stability.

People differ greatly in their abilities to regulate thoughts and behaviors. For example, some people can resist the temptation to eat chocolate cake, whereas others cannot help it even when they are on a diet and know that they should avoid high-calorie foods. Why do people differ in their ability to control their impulses and urges? What are the cognitive and biological underpinnings of such individual differences?

These are the central questions that we have been addressing through our studies of executive functions (EFs)—a set of general-purpose control mechanisms, often linked to the prefrontal cortex of the brain, that regulate the dynamics of human cognition and action. EFs are important to study because they are a core component of self-control or self-regulation ability (or "willpower"), which has been shown to have broad and significant implications for everyday lives (Mischel et al., 2011; Moffitt et al., 2011).

Since our original study (Miyake et al., 2000), we have learned much about individual differences in EFs. In this article, we present what we have learned so far in the form of four general conclusions. Before doing so, however, we explain our approach.

Assessing Individual Differences in EFs

EF is a challenging topic to study: It is not only elusive to define (Jurado & Rosselli, 2007) but also difficult to measure. Although there are several reasons for this measurement difficulty (Miyake et al., 2000), arguably the most vexing problem is the *task-impurity* problem. Because any target EF must be embedded within a specific task context (so that the target EF has something to operate on), any score derived from an EF task—say, the well-known Stroop task (naming the ink color of a color word, such as GREEN, when the color and word are incongruent)—necessarily includes systematic variance attributable to non-EF processes associated with that specific task context (e.g., color processing, articulation speed). Unfortunately, this systematic non-EF variance and measurement error (random noise in the data) are substantial, making it difficult to cleanly measure the EF variance of interest.

To alleviate this task-impurity problem, we use a latent-variable approach. In this approach, one selects multiple exemplar tasks that seem different on the surface but still capture the target ability. If exemplar tasks are chosen such that they share little systematic non-EF variance, one can statistically extract what is common across those tasks (using such multivariate statistical techniques as confirmatory factor analysis and structural

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equation modeling) and use the resulting "purer" latent variable as the measure of EF.

Our research has focused primarily on three EFs: *updating* (constant monitoring and rapid addition/deletion of working memory contents), *shifting* (switching flexibly between tasks or mental sets), and *inhibition* (deliberate overriding of dominant or prepotent responses). Some tasks we use to capture these EFs are illustrated in Figure 1. Although there are other EFs (e.g., dual-tasking) and other levels of analysis that could be justified and explored,[1] these three EFs (updating, shifting, and inhibition) have provided useful insights into the nature and organization of individual differences in EFs.

## Four General Conclusions About Individual Differences in EFs

Unity and diversity

The first conclusion is that individual differences in EFs show both "unity" and "diversity," a notion originally proposed by Teuber (1972). That is, different EFs correlate with one another, thus tapping some common underlying ability (unity), but they also show some separability (diversity). This pattern is illustrated in Figure 2a with data from a large twin sample (Friedman, Miyake, Robinson, & Hewitt, 2011): The correlations among the three EF latent variables are substantial but are far from perfect (i.e., 1.0). This general unity/diversity pattern has been observed in other samples, including preadolescent children (e.g., Rose, Feldman, & Jankowski, 2011) and older adults (e.g., Vaughan & Giovanello, 2010), although only a single unitary factor may be evident in preschool children (e.g., Wiebe, Espy, & Charak, 2008). The diversity of EFs is further supported by the observation that the three EFs differentially relate to other measures, such as well-known neuropsychological tests of frontal-lobe functioning (Miyake et al., 2000) and IQ (Friedman et al., 2006).

Although our work initially focused on how the three EFs relate to one another and to other individual differences measures of interest, our goal has shifted recently to specifying the cognitive and biological underpinnings of the unity and
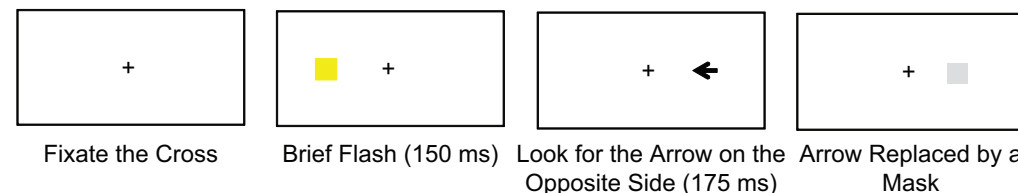
**Updating: Letter Memory Task** (Always Remember the Last 3 Letters)
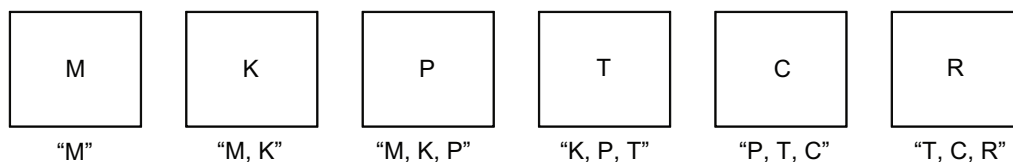
Shifting: Color-Shape Task (Classify Each Target by Color [C] or by Shape [S])
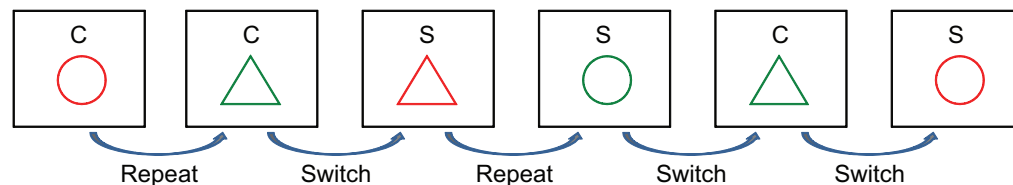
Inhibition: Antisaccade Task (Report the Arrow Direction Presented on the Nonflashed Side)

Fig. 1. Schematic illustrations of three executive function (EF) tasks used in our current EF test battery. In the letter memory task (an example of an updating task), participants are presented with a series of consonant letters one at a time and asked to report the last three letters after the presentation of the letter sequence ends. To ensure that participants constantly update their working memory contents, they are required to say aloud what the last three letters are after each letter. The dependent measure is the accuracy of the recalled letters at the end. In the color-shape task (an example of a shifting task), participants see a letter cue first (either *C* or *S*) and, depending on the cue, they make a classification decision about the target item presented shortly afterward in terms of color (green or red) or shape (circle or triangle) by pressing appropriate buttons on a button box. The dependent measure is the switch cost—namely, a reaction-time difference between switch and repeat trials. In the antisaccade task (an example of an inhibition task), participants first fixate on the center cross. When a brief flash occurs, they need to avoid looking at that flash and instead move their gaze toward the opposite side of the screen so that they can correctly identify and report the direction of an arrow briefly presented there. The dependent measure is the proportion of correctly reported arrows. More procedural details of these tasks and the details of other EF measures we use are provided in Friedman et al. (2008).
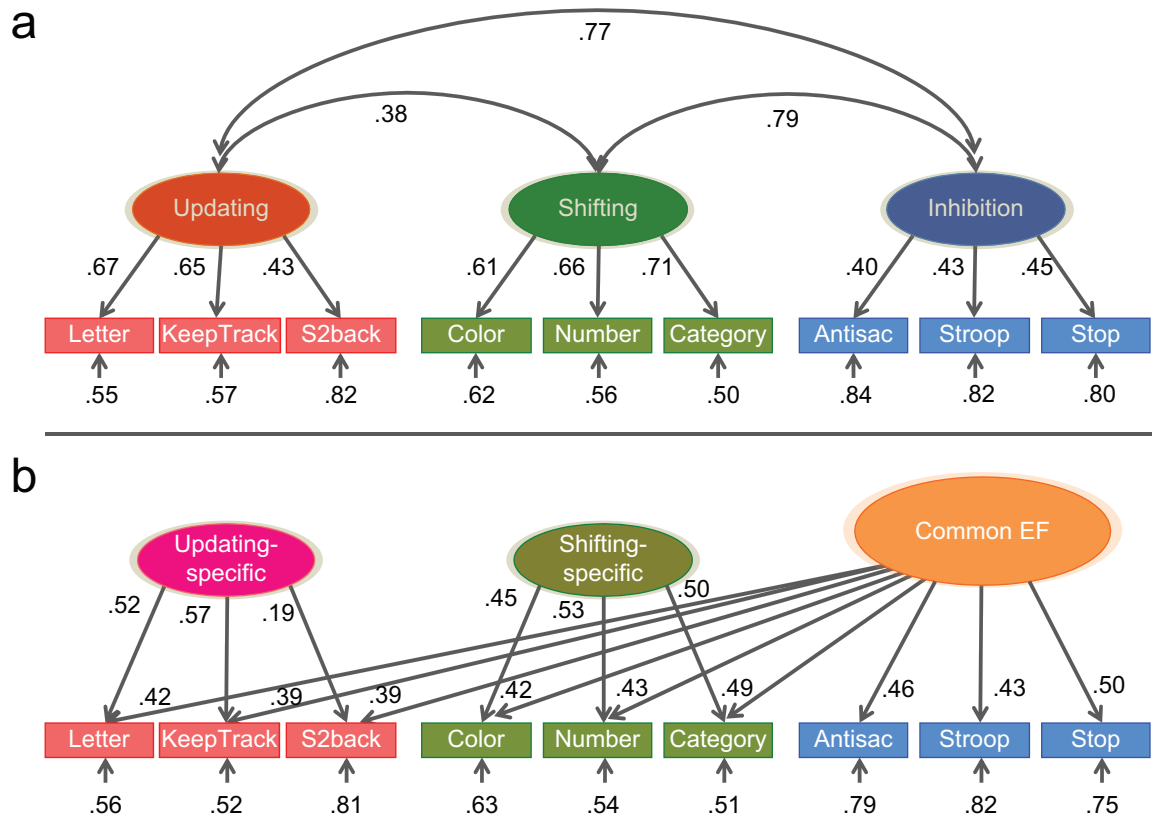
Fig. 2. Two complementary ways of representing the unity and diversity of executive functions (EFs), adapted from the confirmatory factor analysis results reported in Friedman et al. (2011; task names are abbreviated). Numbers on arrows are standardized factor loadings (values from −1 to 1 that indicate the extent to which the individual tasks are predicted by the latent variable), and those under the smaller arrows are residual variances (the variances in the tasks that are not explained by the EF latent variables). Those on curved double-headed arrows are correlations between the EF latent variable factors. Panel a illustrates the unity and diversity of EFs by showing that the three types of EFs (updating, shifting, and inhibition) are substantially correlated with each other (unity) but are separable (diversity) in that those correlations are far from 1.0. This was the way our research initially examined individual differences in EFs (e.g., Miyake et al., 2000). Panel b illustrates the unity and diversity of EFs in a way that is more consistent with the unity/diversity framework we have been developing. As Panel b shows, there is a common EF latent variable on which all nine EF tasks load (unity), as well as two "nested" latent variables on which the updating and shifting tasks, respectively, also load (diversity). Because the common EF variance happened to be perfectly correlated with the inhibition latent variable, no inhibition-specific factor is represented in the figure. Letter = letter memory, Keep = keep track, S2back = Spatial 2-back, Color = color-shape, Number = number-letter, Category = category-switch, Antisac = antisaccade, and Stop = stop-signal (for details about these tasks, see Friedman et al., 2008).

diversity more directly. A new framework—the *unity/diversity* framework—that reflects this recent shift in research goals is illustrated in Figure 3. Each EF ability (e.g., updating) can be decomposed into what is common across all three EFs, or unity (termed common EF), and what is unique to that particular ability, or diversity (e.g., updating-specific ability). Instead of the elements on the left side of the equation that reflect mixed influences from both unity and diversity (updating, shifting, inhibition), the unity/diversity framework focuses on the elements on the right side that may more cleanly map onto the underlying cognitive processes (common EF, updating-specific, and shifting-specific abilities) and seeks to specify their underpinnings.

This new way of examining individual differences in EFs is still under development but has already produced some

interesting discoveries. First, after accounting for the unity (common EF), there is no unique variance left for inhibition (Friedman et al., 2008, 2011), hence the absence of the inhibition-specific factor in Figure 3. Stated differently, the inhibition factor happens to correlate virtually perfectly with common EF, leaving no inhibition-specific variance. This finding, which we have now replicated in two independent college student samples, is shown in Figure 2b. Another discovery, to be illustrated later, is that the common EF and shifting-specific components sometimes show opposing patterns of correlations with other measures, hinting at the multifaceted nature of shifting ability (stability vs. flexibility) suggested in the literature (Goschke, 2000).

Using these findings as clues, we have been developing hypotheses regarding what specific ability each EF component
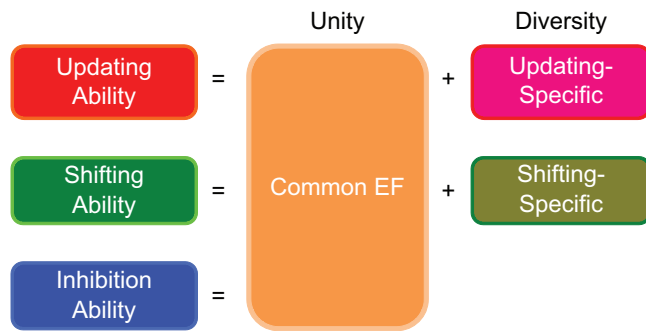
Fig. 3. Schematic representation of the unity and diversity of three executive functions (EFs). Each EF (e.g., updating) is really a combination of what is common to all three EFs (common EF) and what is specific to that EF (e.g., updating-specific ability). Although our initial research has focused on three types of EFs (the left side of the equation) and how they relate to other psychological measures of interest, the unity/diversity framework we have been developing focuses on the right side of the equation (common EF, updating-specific, and shifting-specific abilities) so that we can more directly specify the cognitive and biological underpinnings of the unity and diversity of EFs. In this figure, the inhibition-specific component is absent, because we have found repeatedly that, once the unity (common EF) is accounted for, there is no unique variance left for the inhibition-specific factor, a point also illustrated in Figure 2b in the data from a large twin sample (Friedman et al., 2011).

may be tapping. According to our current view, common EF is about one's ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing. This basic ability is necessary for all three EFs and has also been suggested as a key requirement of response inhibition (Munakata et al., 2011). In contrast, we hypothesize that the shifting-specific component reflects flexibility—ease of transitioning to new task-set representations. At present, we are less certain about what the updating-specific component taps, but two candidate mechanisms are effective gating of information and controlled retrieval from long-term memory.

Substantial genetic contributions

The second conclusion is that individual differences in EFs reflect substantial genetic contributions at the level of latent variables (Friedman et al., 2008). As is commonly done in behavioral genetic analyses, we used correlations from monozygotic (identical) and dizygotic (fraternal) twins to decompose the sources of individual differences in EFs into three components: genetic variance (heritability) and two types of environmental variances (shared and nonshared environments).

The individual tasks showed moderate heritability (.25–.55), with the remaining variance attributable mostly to nonshared environment (which includes measurement error). However, at the level of latent variables, where measurement error is minimized, the heritability estimates were considerably higher (over .75). More important, substantial genetic contributions were observed at both unity and diversity levels, suggesting that separate sets of genes contribute to the variability in common EF versus updating-specific and shifting-specific abilities. Such

results hold promise for current efforts linking specific genes to EFs (see Barnes, Dean, Nandam, O'Connell, & Bellgrove, 2011, for a recent review), but also point to the complexity of the EF genetic structure.

We should emphasize here that high heritability does not mean immutability. Heritability is the portion of variability *across individuals within a particular sample* attributable to genetic effects *at a particular point in time*. Thus, it says nothing about the source(s) of a particular individual's EF ability or the trainability of EFs within each individual or among a group of individuals. In fact, recent studies suggest that EF ability is amenable to some training effects (e.g., Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008), although the transferability of training effects across different types of EF tasks and cognitive measures (e.g., fluid intelligence) has not been clearly established yet.

Clinical and societal relevance

The third conclusion is that purely cognitive measures of EFs can predict individual differences in clinically and societally important behaviors (Friedman et al., 2007, 2011; Young et al., 2009). In particular, recent evidence points to the unity component of EFs (common EF) as the primary source of such predictive power.[2]

An illuminating example comes from the twin data on *behavioral disinhibition* (Young et al., 2009). Behavioral disinhibition is a general vulnerability factor hypothesized to underlie different types of so-called externalizing behavior problems, such as attention deficits (often shown by individuals with attention deficit hyperactivity disorder), novelty seeking/risk taking, conduct disorder, and substance use. A latent variable for behavioral disinhibition was substantially correlated (−.63) genetically with the common EF variable (the phenotypic or nongenetic correlation was −.35), indicating that better general EF ability is associated with fewer such behavioral problems.[3]

More generally, recent research has yielded substantial evidence that links individual differences in EFs to diverse self-regulatory behaviors, such as the expression and control of implicit racial biases and prejudice (e.g., Klauer, Schmitz, Teige-Mocigemba, & Voss, 2010; Stewart, von Hippel, & Radvansky, 2009), staying faithful to romantic partners (e.g., Pronk, Karremans, & Wigboldus, 2011), and successfully implementing dieting and exercising intentions (e.g., Hall, Fong, Epp, & Elias, 2008). These findings from various subdisciplines of psychological science suggest that those simple lab-based EF tasks illustrated in Figure 1 are capturing something important and meaningful, especially at the level of latent variables.

Developmental stability

The final conclusion is that individual differences in EFs show some stability during development. In our research, this conclusion has emerged from two lines of longitudinal analyses.

The first concerns the 6-year stability of EFs in the twin sample, measured at ages 17 and 23, during which many twins moved out of their parents' homes and started to live separately. Preliminary results indicate that, despite such major life changes, the age-17/age-23 correlations are substantial at the level of latent variables (.82 for common EF, 1.00 for updating-specific ability, and .93 for shifting-specific ability).

The second line of evidence takes advantage of the fact that we have been tracking our twin sample from their infancy. Specifically, we have been trying to identify early measures that could predict later individual differences in EFs. The earliest precursor we discovered is a simple measure of self-restraint during toddlerhood (Friedman et al., 2011). In this study, self-restraint was assessed with a prohibition task, in which a child was shown an attractive toy (a glitter wand) and then told not to touch it for 30 seconds, a task that has conceptual similarities to the well-known delay-of-gratification tasks (Mischel et al., 2011) and requires active goal maintenance (e.g., maintaining a goal of not touching a toy).

Based on growth modeling of four testing occasions (ages 14, 20, 24, and 36 months), we identified two distinct developmental trajectories, shown in Figure 4. Remarkably, this group difference was still evident at age 17: The better-self-restraint group demonstrated significantly *better* common EF (by .60 standard-deviation, *SD*, units), virtually no difference in the updating-specific ability (.05 *SD*s better), and significantly *worse* shifting-specific ability (.42 *SD*s worse) than did the worse-self-restraint group. Together with other longitudinal data (Mischel et al., 2011; Moffitt et al., 2011), these results suggest that individual differences in self-regulation and EF abilities are relatively stable developmentally. Considering that all participants' overall self-regulation and EF abilities undoubtedly improved substantially during this 14-year span, this example illustrates that such stability of individual differences does not necessarily mean no change in EF abilities within individuals.

The evidence of worse shifting-specific ability associated with better childhood self-restraint may be counterintuitive, but it illustrates something we alluded to earlier: The two components of shifting ability—common EF and shifting-specific abilities—sometimes show opposing patterns of correlations with other constructs. As Goschke (2000) suggested, the ability to actively maintain a single task goal may indeed be a force that makes it difficult for individuals to flexibly switch to a different goal.

Current and Future Research Directions: Specifying the Biological Basis of EFs

In this review, we presented four general conclusions that concisely capture what we have learned about individual differences in EFs. As we illustrated here, individual differences in

Fig. 4. Growth trajectories of the two groups identified in the latent class growth model illustrating the development of self-restraint ability, as measured by a simple prohibition task (Friedman et al., 2011). In this task, a child is shown an attractive toy and then told not to touch it for 30 seconds. One group (55% of the sample) showed better self-restraint than the other group (45%), and this group difference was significant at all four time points (14, 20, 24, and 36 months of age). As explained in the main text, this group difference was also reflected in their performance of executive function (EF) tasks, assessed 14 years later at age 17. For simplicity, the figure shown here is based on the data from dichotomous scoring of the prohibition task performance (pass or fail). The analyses and results reported in the Friedman et al. (2011) article take into account the durations for which each child was able to not touch the toy.

EFs are highly relevant to many different subdisciplines of psychological science and hence could have broad implications for both basic and applied research. In this regard, we are currently examining how individual differences in EFs relate to various important phenomena in psychology, such as cognitive control in depression and anxiety (Altamirano, Miyake, & Whitmer, 2010), the expression and control of implicit racial bias, and the regulation of substance use and eating behavior.

We believe that the unity/diversity framework described here provides a useful basis for examining individual differences in EFs in future research. To make the framework even more useful, however, we have been developing the main ideas computationally and trying to link the behavioral, cognitive, and genetic levels of our theoretical explanations more tightly. We end this article by describing such current efforts.

To better understand the neural and genetic mechanisms underlying individual differences in EFs, we are using neural-network modeling in the context of the prefrontal-cortex basal-ganglia working-memory (PBWM) model developed by O'Reilly and colleagues (O'Reilly & Frank, 2006). PBWM provides a biologically plausible model of the brain areas involved in EFs, which exhibit specific properties constrained by known biology. The prefrontal-cortex layer can actively maintain relevant information through persistent activation and recurrent connectivity. Because it can bias lower-level activity through its connections to posterior-cortex layers, which do not have these same active maintenance mechanisms, it is particularly suited to maintaining goals and using these goals to bias ongoing processing. Information is flexibly gated into the prefrontal-cortex layer through the basal-ganglia layers, which learn what information is relevant through dopaminergic reward-learning mechanisms.

Using this domain-general PBWM model, we have been simulating the EF tasks used in the Friedman et al. (2008) study and manipulating model parameters to test our hypotheses about the mechanisms influencing individual differences (see Chatham et al., 2011, for a detailed report of our simulation of the *n*-back task, one of the updating tasks in our EF battery). For example, in this ongoing work, to simulate individual differences in hypothesized common EF mechanisms of actively maintaining goals and thereby biasing lower-level processing, we manipulated parameters that influence the strength of representations in the prefrontal-cortex layer of the model and how strongly the prefrontal cortex connects with posterior areas. Consistent with our hypothesis that goal maintenance is important for all EFs, these manipulations affected all the modeled tasks. In contrast, manipulations of other parameters in the prefrontal-cortex layer that influenced how long representations persist after they are no longer needed affected only the shifting tasks, consistent with our hypothesis that the shifting-specific factor may reflect the ease of transitioning to new representations in the prefrontal cortex. Hence, we have begun to replicate the unity/diversity pattern observed behaviorally with this biologically constrained model.

An ultimate goal of this computational modeling is to develop hypotheses for testing specific genes that contribute to individual differences in these EFs. Although previous studies have examined the roles of particular genetic variants (especially within the dopamine system), the effects are typically small and often do not replicate (Barnes et al., 2011). One promising approach is to test aggregate effects of multiple genes that, when combined, have larger effects on biological parameters. Because the model can simulate the effects of multiple genetic variants acting independently or even jointly, it can provide a strong theoretical framework with which to develop detailed hypotheses regarding the genetic influences underlying the unity and diversity of EFs.

Recommended Reading

Barnes, J. J. M., Dean, A. J., Nandam, S., O'Connell, R. G., & Bellgrove, M. A. (2011). (See References). Provides an in-depth review of recent molecular genetic (polymorphism) research examining the genetic correlates of EFs, including response inhibition, in both clinical (e.g., ADHD) and nonclinical populations.

Braver, T. S., Cole, M. W., & Yarkoni, T. (2010). Vive les differences! Individual variation in neural mechanisms of executive control. *Current Opinion in Neurobiology, 20*, 242–250. Provides a concise review of recent cognitive neuroscience research (including neuroimaging work) on individual differences in EFs.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*, 959–964. Provides a concise yet broad-scope review of various intervention efforts to improve children's EF abilities.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 18*, 893–900. Reports a study demonstrating that different types of inhibition do not necessarily correlate with one another and, hence, should not be treated interchangeably.

Miyake, A., Emerson, M. J., & Friedman, N. P. (2000). Assessment of executive functions in clinical settings: Problems and recommendations. *Seminars in Speech and Language, 21*, 169–183. Provides a readable tutorial on various challenges facing the measurement of EFs and offers some concrete recommendations.

Acknowledgments

Declaration of Conflicting Interests

Funding

Notes

1. For example, a commonly postulated EF, *planning*, is a more complex and higher-level construct than those we study and is likely to implicate all three EFs. Each of the three EFs, in turn, could be decomposed into multiple subprocesses (e.g., monitoring, item addition, active maintenance, and item deletion for updating) and studied at this more fine-grained level if appropriate tasks are available to tap individual differences in those subprocesses.

2. Interesting to note, individual differences in cognitive abilities, such as IQ, are most strongly related to updating ability (Friedman et al., 2006). In fact, both common EF and updating-specific ability are equally strongly related to IQ (Friedman et al., 2008), suggesting that common EF is not the same as so-called general intelligence (*g*).

3. The original publication of this study (Young et al., 2009) reported that, among the three EFs, inhibition correlated most strongly with behavioral disinhibition. The result reported here is based on a reanalysis of the data using the unity/diversity framework.

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