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Developmental Science and Executive Function

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Abstract
Executive function abilities, including working memory, inhibitory control, and the flexible volitional shifting of the focus of attention, provide a foundation for reflection on experience, reasoning, and the purposeful regulation of behavior. These abilities and their underlying neurobiology, however, are inherently malleable and influenced by characteristics of individuals and contexts. Implications of this malleability for research on the development of executive function in early childhood, for the prospect that these abilities can be fostered and promoted by specific types of activities, and for issues relating to the reliable and valid measurement of executive function are considered.

Keywords
executive function, childhood development, education, stress, emotion, attention, plasticity, measurement

Executive function (EF), defined as the ability to hold information in working memory, to inhibit fast and unthinking responses to stimulation, and to flexibly shift the focus of one's mental frame, is more or less the foundation for the intentional, volitional self-directed control of behavior. The cognitive skills that make up this construct help us to limit impulsive responses, to regulate emotions, and to avoid bad decisions that might bring short-term gain but longer-term problems. On the more positive side, these thinking skills contribute to the basis for doing well in school and work, solving problems and planning ahead, and leading our lives in ways that make them a little easier and less chaotic.

Given the advantages of EF, the purpose of this essay is to describe an approach to the construct that is grounded in developmental science and the neurobiology of cognitive control, and to use this approach to illuminate some current research directions. One such direction concerns construct definition and differentiation of EF from other aspects of self-regulation. A second concerns the relation of EF to stress, particularly for individuals facing high levels of social and economic disadvantage. A third concerns the trainability of EF. A fourth and overarching direction concerns the reliability and validity of EF assessments.

A Little Neurobiology

Executive functions, particularly working memory, have been the bread and butter of cognitive neuroscience, and relations between brain activity and EF behavior are well established. For example, it is well established that specific aspects of EF are associated with specific areas of prefrontal cortex (PFC) and that these areas of PFC are interconnected with numerous regions throughout the brain, including other cortical regions but also, most importantly for present purposes, subcortical structures associated with emotional reactivity, the control of attention, and the stress response (Barbas & Zikopoulos, 2007). In brief, the subcortical areas very rapidly (prior to conscious awareness) register stimulation. In turn, activity in the subcortex signals to PFC through neurochemical messengers (neurotransmitters), some which are associated with the stress response and, generally speaking, help to direct our attention and thinking skills to things that are meaningful to us and away from things that are not. In a word, the interconnected lower-brain-to-higher-brain circuitry underlies the goal-directed, purposeful nature of EF.

Which is all well and good when stimulation leads to responses in emotion and attention systems and to an increase in neurotransmitters, dopamine and norepinephrine, that are in a moderate range. The relation of EF

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to emotion and stress, however, is a double-edged sword (Arnsten, 2009). Just as a moderate increase in dopamine and norepinephrine facilitates activity in neurons in PFC and thereby facilitates EF, too much of an increase, indicating that the person is stressed out and overstimulated, or too little of an increase, indicating boredom and lethargy, inhibits neural activity in PFC and, consequently, the valuable thinking skills that this activity supports. To be clear, this neurobiology has been most specifically demonstrated in nonhuman primates for the spatial working memory aspect of EF (Vijayraghavan, Wang, Birnbaum, Williams, & Arnsten, 2007). The process, however, applies to PFC generally and is one in which chronic stress has been shown in animal models to reduce the size and density of neurons in PFC and to lead to impairments in cognitive flexibility as well as working memory (Holmes & Wellman, 2009).

EF and Self-Regulation

One implication of the neurobiology outlined above is to consider EF as one component of a larger system of self-regulation. A narrow definition might equate EF and self-regulation on the premise that self-regulation refers only to the intentional and conscious control of behavior. The developmental approach, however, recognizes that regulation of the stress response and of emotion and attention can and does occur outside of conscious awareness, perhaps exclusively so in the infant and toddler period, with implications for the development of the conscious control of behavior through EF. Here, self-regulation is understood as a recursive system (Luu & Tucker, 2004)—both volitional and top-down as well as non-volitional and bottom-up. This recursive approach is premised on the neurobiology described above and indicates that "higher-level" EF abilities both affect and are affected by "lower-level" processes associated with the automatic, nonconscious management of emotional and physiological responses to stimulation. The focus on recursive relations between volitional and non-volitional influences is also seen in Zelazo's (Cunningham & Zelazo, 2007) Iterative Reprocessing Model, in which intentional, top-down EF is understood to emerge from repeated, iterative, bottom-up automatic processing of information.

A focus on levels of analysis in research on EF and self-regulation helps to differentiate EF from related constructs. EF is to some extent synonymous with effortful control, delay of gratification, and emotion regulation. Behavior in each of the latter constructs, however, can be parsed into intentional and non-intentional (habitual) components. That is, we can regulate emotion and resist gratification through the intentional control of behavior using EF but also employ less intentional strategies to regulate emotion and behavior, particularly in childhood (Cole, Martin, & Dennis, 2004). To the extent to which an individual employs intentional control of attention and holds information in mind when regulating emotion or resisting temptation, these would be considered executive tasks.

The focus on levels of analysis in the developmental-science approach also has implications for understanding the development of EF. Although some studies have shown that EF types of abilities are present very early in life (Kovács & Mehler, 2007), a small number of longitudinal studies have shown that individual differences in attention, emotion, and the physiological response to stress in infancy and the toddler period predict later EF. In one, visual-recognition memory and processing speed in infancy were uniquely related to EF at 11 years (Rose, Feldman, & Jankowski, 2012). In another, observed emotional reactivity to a scary mask at 15 months combined with behaviors indicative of the regulation of emotion (e.g., avoidance, self-soothing) was associated with better EF at 4 years (Ursache, Blair, Stifter, Voegtline, & The FLP Investigators, 2013). In a third, communicative gestures at 15 months and language at 2 and 3 years were highly predictive of EF at age 4 (Kuhn et al., 2014). Of course, these longitudinal relations among constructs do not imply causality. They are, however, consistent with a developmental theory in which complex intentional behavior arises from less complex, less intentional behavior.

EF in the Context of Poverty

A further research direction addressed by the developmental science approach and the neurobiology on which it is based concerns the idea that EF skills can be hard to come by when we need them the most, particularly for individuals in poverty and other highly stressful contexts. Our nervous systems are wired in such a way that when under stress, we are more reactive and less reflective. From the 20/20 hindsight of evolutionary explanations for behavior, this makes sense. When an urgent situation requires an immediate response (think encountering a predator at the watering hole or an intruder in your home), reflecting on the situation will probably only compound the problem.

Such an understanding of EF leads to some specific hypotheses about the relation of early experience to the development of EF. Two longitudinal studies have shown that the physical and psychosocial characteristics of poverty are physiologically stressful for young children, altering hormone levels and making the stress response less flexible (Blair, Raver, et al., 2011; Evans, 2003). In turn, such effects of experience on the stress response have been shown to partially mediate the effects of socioeconomic disadvantage on EF abilities in childhood (Blair, Granger, et al., 2011; Evans & Schamberg, 2009). In one of these (Blair, Granger, et al., 2011), the effect of poverty on EF at age 3 was partially mediated through parenting quality. In another (Evans, Kim, Ting, Tesher, & Shannis, 2007), a supportive relationship with the mother was found to moderate effects of poverty on EF in early adolescence. Given the centrality of EF to school readiness and achievement, such shaping of EF in childhood would appear to be a primary contributor to poverty-related gaps in school readiness and school achievement (Blair & Raver, 2015).

Trainability of EF

If EF can be compromised under conditions of disadvantage, both developmentally and at a given point in time, then EF should equally well be supported under favorable conditions. Identifying the parameters of this malleability and the extent to which it might be greater at some points during development than others (i.e., sensitive periods) is a major research goal. To date, the malleability of EF has been primarily demonstrated through various training approaches that for purposes of this review can be classified as direct versus indirect. Direct training involves repetitive practice on a specific EF task, usually a working memory task, in which improvement in performance on that task is the goal (Klingberg, 2010). Indirect training involves repetitive practice on activities that exercise EF, such as learning mathematics or martial arts, in which becoming better at math or becoming a martial arts master is the goal.

Training approaches, both direct and indirect, have been comprehensively reviewed (e.g., Diamond & Lee, 2011; Melby-Lervåg & Hulme, 2013), most extensively in the instance of direct training. With few exceptions (Shipstead, Redick, & Engle, 2012), the general conclusion of these reviews is that training works. Direct training, however, has produced an interesting set of findings in which training results in near transfer, whereas findings for far transfer are mixed.

Without question, effects of direct training of working memory are impressive. Changes in performance are frequently accompanied by changes in aspects of the neural circuitry that supports EF. Given mixed results for far transfer, however, perhaps indirect training—that is, training in which EF practice is embedded in activities in which EF will ultimately be put to use—will be most effective. Evidence in support of this idea is found in randomized controlled trial (RCT) evaluations of school readiness and early education programs focusing for the most part indirectly on EF (although see Schmitt, McClelland, Tominey, & Acock, 2015, for something of an exception). Evaluations of programs focusing on the regulation of emotion and attention as well as on EF in the school context have generally yielded positive results not only on measures of EF but also on academic and social-emotional outcomes. Two approaches have focused on emotion regulation and the regulation of behavior in preschool classrooms with children in poverty (Bierman et al., 2008; Raver et al., 2009), with one of these demonstrating that the program led to increases in EF and, through EF, higher levels of academic ability in preschool (Raver et al., 2011). Similar results are seen in evaluations of high-quality pre-K and kindergarten programs that emphasize child-directed learning and exploration, such as Tools of the Mind (Bodrova & Leong, 2007) and Opening the World of Learning (Schickedanz & Dickinson, 2005). Evaluations of these programs have yielded effects on EF as well as academic outcomes (Blair & Raver, 2014; Weiland & Yoshikawa, 2013).

There is still much to be learned about conditions under which EF can be improved and the extent to which educational approaches focusing on EF can be expected to affect children's academic progress. For example, two recent meta-analyses examining relations between EF and academic achievement (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Jacob & Parkinson, 2015) came to opposite conclusions, and a recent a large-scale evaluation of the Tools of the Mind prekindergarten program found no effects of the program on any aspect of children's development (Wilson & Farran, 2012). Research is needed on variation in the effectiveness of EF training, both direct and indirect. Individual differences in children's initial EF skills could be one such influence, as well as variation in EF in children's caregivers, including teachers as well as parents.

Measurement of EF

Finally, the developmental science approach helps to address the long-standing issue that measures of EF tend to correlate moderately at best and not at all at worst (Rabbitt, 1998). With one or two notable exceptions (Zelazo et al., 2013), this leads to a situation in which observed score composites of two or more EF tasks tend to have poor internal-consistency reliability and retest reliability (Carlson, Mandell, & Williams, 2004; Willoughby, Pek, Blair, & The FLP Investigators, 2013). This is troubling, in that for most psychological constructs, a greater number of measures tends to increase the reliability of measurement. Researchers have attempted to circumvent this state of affairs using confirmatory factor analysis and provide persuasive evidence that EF in early childhood is composed of a single latent factor (Wiebe, Espy, & Charak, 2008). Unfortunately, even in the instance of excellent global model fit, the reliability of the observed indicators places an upward limit on the reliability of the latent factor (Willoughby et al., 2013).

Issues with reliability could indicate that measures of EF are poor measures of the construct, or even that the construct is poorly defined and operationalized. More likely, however, moderate reliability is indicative of the inherent malleability of EF and, in early childhood, a consequence of the rapid pace of EF development (Carlson, 2005). Given that EF is to some extent dependent on lower-level processes and moderate levels of physiological stimulation, it is understandable that performance on a battery of EF tasks in a given assessment session might show uneven levels of performance within and between individuals. Momentary lapses in attention that are systematically related to the location of a given task in a battery of EF tasks and a tendency to respond reflexively and automatically to some but not to other tasks would produce low internal-consistency reliability. Much the same applies to estimates of retest reliability. One possible solution would be to shorten task batteries, and also to focus specifically on a single dimension of EF, such as working memory or the flexible shifting of attention. Doing so, however, would not necessarily result in higher correlations among tasks or better retest reliability.

Conclusion

Ongoing research to identify sources of within- and between-person variability in EF, including aspects of experience as well as more traitlike aspects of the person, such as temperament, personality or even genetic markers, can address key questions about the malleability of the construct. A focus on variability and malleability will have implications for all of the research directions discussed here, including construct differentiation, the relation of stress to EF, the use of research on EF as a basis for educational practice (Blair & Raver, 2015), and the measurement of EF (Willoughby, Holochwost, Blanton, & Blair, 2014). In sum, research on EF and related aspects of self-regulation can play an integrative role in psychological science (Posner & Rothbart, 2007). It can help unite distinct but interrelated areas of research in a comprehensive approach to human development that serves as a basis for action, putting science to work to promote well-being.

Recommended Reading

Arnsten, A. F. T. (2009). (See References). A comprehensive and fascinating review of the neurobiology of prefrontal cortex and of the author's research demonstrating that alteration of catecholamine levels in the brain affects neuronal activity, with implications for working memory abilities.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. An excellent overview of executive function abilities, their centrality to everyday life, and current controversies in research on executive function.

Fuster, J. M. (2008). *The prefrontal cortex* (4th ed.). San Diego, CA: Academic Press. Required reading for a comprehensive understanding of the neuroanatomy and neurobiology of the "seat of higher-order cognitive functions."

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). (See References). An insightful and highly readable review of the working memory training literature that identifies several methodological points not previously considered or addressed.

Vohs, K. D., & Baumeister, R. (Eds.). (2011). *Handbook of self-regulation: Research, theory, and applications* (2nd ed.). New York, NY: Guilford Press. An edited volume that provides perspective on the multiple and various conceptual models of self-regulation across several different academic disciplines and programs of research addressing each.

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