Hot and Cool Executive Function in Childhood and Adolescence: Development and Plasticity

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ABSTRACT—***Executive function (EF), which refers to the more deliberate, top-down neurocognitive processes involved in self-regulation, develops most rapidly during the preschool years, together with the growth of neural networks involving prefrontal cortex but continues to develop well into adulthood. Both EF and the neural systems supporting EF vary as a function of motivational significance, and this article discusses the distinction between the top-down processes that operate in motivationally and emotionally significant situations ("hot EF") and the top-down processes that operate is more affectively neutral contexts ("cool EF"). Emerging evidence indicates that both hot and cool EF are surprisingly malleable, with implications for intervention and prevention.***

KEYWORDS—*executive function; prefrontal cortex; emotion; neural plasticity; intervention*

> Generally youth is like the first cogitations, not so wise as the second.
>
> Francis Bacon, *Of Youth and Age*

Executive function (EF), also called cognitive control, refers to the deliberate, top-down neurocognitive processes involved in the conscious, goal-directed control of thought, action, and emotion—processes that include cognitive flexibility, inhibitory control, and working memory (Miyake et al., 2000). As shown in Figure 1, research using measures of EF that are suitable for participants aged 3–85 years suggests that EF improves most rapidly during the preschool period but continues to develop during adolescence (and beyond; Zelazo et al., in press). These changes in EF co-occur with substantial structural and functional changes in neural systems involving prefrontal cortex (Carlson, Zelazo, & Faja, in press).

Interest in the development of EF has increased dramatically during the past decade, as reflected in a fivefold increase in the number of publications on this topic (Carlson et al., in press). One reason for this increased interest is that individual differences in EF measured in childhood have been found to predict important developmental outcomes. For example, in a follow-up to their seminal work on delay of gratification at Stanford's Bing Nursery School in the 1970s, Mischel and colleagues examined adolescents who as children in the study had either refrained from eating a marshmallow in order to receive a larger reward 15 min later or had failed to wait—an important index of childhood EF. Adolescents who had delayed gratification as children were judged by parents and peers to be more interpersonally competent, and they demonstrated better concentration, self-control, and frustration tolerance (Mischel, Shoda, & Rodriguez, 1989; Shoda, Mischel, & Peake, 1990). They also scored significantly higher on the Scholastic Aptitude Test (SAT), independent of IQ, and as adults, they were less likely to use recreational drugs (Ayduk et al., 2000). A more recent report of individuals from a different longitudinal study found that self-control—a construct that overlaps considerably with EF—measured between ages 3 and 11 years predicted (as a gradient) physical health, substance dependence, socioeconomic status (SES), and the likelihood of a criminal conviction at age 32 years, even after controlling for social class of origin and IQ (Moffitt et al., 2011). Together, the evidence suggests long-term stability of early individual differences in EF that have meaningful consequences for people's lives.

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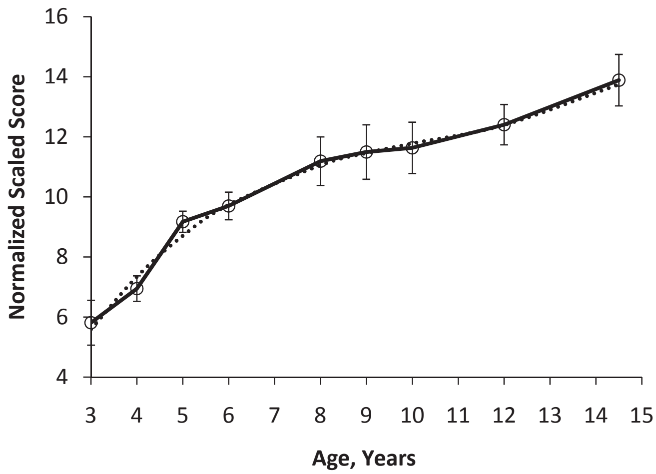

Figure 1. Performance on the NIH Toolbox DCCS Test across age groups.
Note. Pediatric data are from a cross-sectional validation study of 476 individuals aged 3–85 years. Error bars are ±2 *SE*. Also shown is the best fitting polynomial model (cubic, R^2 = .76), which indicates two periods of relatively rapid growth (preschool and early adolescence). Source: Zelazo et al. (in press).

In this article, we address two key issues for future research on EF: the role of motivational significance in EF and the degree to which EF is malleable. Both EF and the neural systems supporting EF vary as a function of motivational significance, and a distinction has been made between the more "cool," cognitive aspects of EF usually associated with lateral prefrontal cortex and the relatively "hot," affective aspects of EF usually associated with orbitofrontal cortex and other medial regions (Happaney, Zelazo, & Stuss, 2004; Zelazo & Müller, 2002). In addition, although there are relatively stable individual differences in both hot and cool EF, there is also growing evidence that EF is surprisingly malleable, with implications for intervention and prevention.

HOT AND COOL ASPECTS OF EF

Traditionally, EF has been examined using abstract, decontextualized problems that lack a significant affective or motivational component. For example, in the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948), widely regarded as "the prototypical EF task in neuropsychology" (Pennington & Ozonoff, 1996, p. 55), participants are given test cards that vary on three dimensions (shape, color, and number) and are required to discover the rules for sorting these cards correctly. Although participants are given feedback, the task does not involve obvious rewards or punishers—there is little to be gained or lost. Reliance on tasks such as the WCST and other well-established measures of EF, including the classic Color-Word Stroop task (Stroop, 1935), versions of the Eriksen flanker task (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005), and the Dimensional Change Card Sort (DCCS; Zelazo, 2006), have supported characterizations of EF and its development that emphasize its more "cool" cognitive features.

In contrast to this emphasis on cool EF, more recent research has employed a broader characterization of EF that also includes the top-down control processes that operate in motivationally and emotionally significant high-stakes situations—what has been called "hot EF" (Zelazo & Müller, 2002). The distinction between hot and cool EF is similar in some respects to the "hot–cool systems" distinction made by Metcalfe and Mischel (1999), although it is also fundamentally different: In the Metcalfe and Mischel (1999) framework, hot processes are not EF processes at all but rather are bottom-up emotional influences on behavior (e.g., associated with the amygdala, not orbitofrontal cortex), which, in fact, tend to undermine top-down processes. In contrast to the hot–cool systems framework, and indeed contrary to a more general assumption that emotional contexts merely elicit stronger bottom-up influences or undermine top-down control, the construct of hot EF captures the suggestion that motivationally significant contexts also demand *different* top-down processes.

The construct of hot EF is supported by neuroscientific research on the functions of orbitofrontal cortex, which is involved in the flexible reappraisal of the affective or motivational significance of stimuli (e.g., Rolls, 2004). The requirement that representations of specific stimulus–reward associations be modified is common to a wide range of measures shown to depend on orbitofrontal cortex (see Happaney et al., 2004, for a review), including measures of reversal learning (in which a rewarded approach–avoidance discrimination must be reversed), delay discounting (in which the value of an immediate reward must be reconsidered relative to larger delayed reward), extinction (in which a previously rewarded stimulus is no longer rewarded and must now be avoided), and gambling (in which what initially appears to be advantageous is revealed over time to be disadvantageous).

Lesion studies involving human and nonhuman animals indicate clearly that hot EF is dissociable from EF as it is traditionally measured (i.e., as cool EF). That is, impairments in hot EF, as assessed by measures of gambling (e.g., Bechara, Damasio, Damasio, & Anderson, 1994), risky decision making (e.g., Rogers et al., 1999), and delay discounting (e.g., Elliott, Frith, & Dolan, 1997), among other measures, can occur in the absence of impairments of cool EF and vice versa. For example, considerable research with both adult and pediatric patients (e.g., Bechara, 2004; Eslinger, Flaherty-Craig, & Benton, 2004) has shown that patients with damage to orbitofrontal cortex are often unimpaired on classic measures of EF (e.g., the WCST) but nonetheless have considerable problems in their daily lives and on measures such as the Iowa Gambling Task. In an initial study with the gambling task (Bechara et al., 1994), adult patients and healthy controls were presented with four decks of cards and told to turn over cards one at a time from any of the decks. After each card was turned, the participants were informed that they had won either $100 or $50 (play money) and, with some cards, that they were also being assessed a penalty. Two decks were advantageous, and two were disadvantageous. Whereas cards from the disadvantageous decks always provided the higher reward ($100), the variable (and unpredictable) penalty losses were much larger on average than the gains. The advantageous decks yielded an overall net gain. Bechara et al. (1994) found that over trials, controls were increasingly likely to select from the advantageous decks, whereas patients were more likely to select from the disadvantageous decks. Impairments on the Iowa Gambling Task have also been documented in pathological gamblers (Cavedini, Riboldi, Keller, D'Annucci, & Bellodi, 2002) and individuals abusing cocaine (Monterosso, Ehrman, Napier, O'Brien, & Childress, 2001), heroin (Petry, Bickel, & Arnett, 1998), alcohol (Mazas, Finn, & Steinmetz, 2000), and a combination of drugs (Bechara et al., 2001; Grant, Contoreggi, & London, 2000).

It should be noted that although hot and cool EF can be dissociated in lesioned brains, they typically work together as part of a more general adaptive function. Indeed, one of the primary ways in which individuals solve motivationally significant problems is to step back and reflect upon them, contextualize them, and consider them in the abstract (Zelazo & Cunningham, 2007). There is also considerable overlap among the neural systems underlying hot and cool EF. Right ventrolateral PFC, for example, appears to play a role in a wide range of situations, including what might be considered both hot and cool contexts (Aron, Robbins, & Poldrack, 2004).

Considering the development of EF in more affectively relevant, hot situations extend the construct of EF to everyday decision making, which is rarely conducted in the absence of motivational and emotional influences, and it provides a new way to make sense of observed differences in performance on relatively hot versus cool versions of the same task. For example, using a delay-of-gratification paradigm, Prencipe and Zelazo (2005) found that 3-year-old children were more likely to choose a larger, delayed reward over a smaller, immediate one when asked which reward the experimenter should choose (cool version) but were more likely to select the immediate reward when asked to choose for themselves (hot version). Similarly, 3-year-olds, but not 4-year-olds, have difficulty when required to point to a smaller reward (e.g., two jelly beans) rather than a larger reward (e.g., five jelly beans) in order to get the larger reward, but Carlson and colleagues found that when the rewards were replaced with abstract symbols (i.e., "cooler" representations of the rewards), 3-year-olds' performance improved significantly (Carlson, Davis, & Leach, 2005). Although a reasonable interpretation of these findings is that the hot versions are simply harder (e.g., because children face a stronger temptation), it is also possible that the hot versions place greater demands on orbitofrontally mediated hot EF and that the development of hot EF may lag behind that of more lateral-prefrontal cool EF.

Although these particular tasks are readily accomplished by older children, similar distinctions between hot and cool EF can be observed in more challenging situations in older participants (e.g., risky decision making for self vs. other during the transition to adolescence; Crone, Bullens, van der Plas, Kijkuit, & Zelazo, 2008). Moreover, in another recent follow-up to the Bing Nursery School sample, Casey et al. (2011) found that delay of gratification in preschoolers was related to performance on a Go/No-Go task 40 years later, but only when participants were required to suppress responses to happy faces (rewarding stimuli), not when required to suppress responses to neutral or fearful faces. Again, although it is reasonable to attribute these patterns to differences in bottom-up influences (e.g., heighted reward sensitivity when deciding for self vs. other), the patterns may also reflect the relatively protracted development of hot EF relative to that of cool EF.

IMPORTANCE OF HOT EF DURING THE TRANSITION TO ADOLESCENCE

There is some suggestive evidence from direct comparisons of cool and hot EF that the development of hot EF lags behind (Bunge & Crone, 2009; Zelazo, Qu, & Kesek, 2010). For example, Hooper, Luciana, Conklin, and Yarger (2004) tested children aged 9–17 years on a measure of hot EF, the Iowa Gambling Task, and two measures of cool EF, Digit Span and a Go/No-Go task. The results revealed age-related improvements in performance on all three tasks, but whereas improvements on Digit Span and Go/No-Go were seen between the two youngest age groups, only the oldest adolescents (aged 14–17) performed well on the Iowa Gambling Task. Similarly, Prencipe et al. (2011) tested children aged 8–15 years and reported that adult-like levels of performance were reached on hot EF measures (including the Iowa Gambling Task) at an older age than was the case for cool EF measures. In both studies, hot and cool measures were weakly correlated. Together, these results are consistent with the possibility that hot and cool EF may develop somewhat independently into adolescence and that hot EF may follow a different, perhaps delayed, trajectory of development relative to that of cool EF. If so, this could help explain the above-mentioned discrepancies between adolescents' theoretical understanding of the potential negative consequences of their behavior and their real-life choices in emotion-laden situations (e.g., in the face of peer pressure).

Although the distinction between hot and cool EF is well supported by lesion studies and neuroimaging research, and is evident in behavioral research with adolescents and adults, further research is needed on its emergence in childhood. A number of studies with young children have found that hot and cool EF load onto distinct (but correlated) factors (e.g., Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Carlson, Moses, & Breton, 2002; Davis-Unger & Carlson, 2008; Willoughby, Kupersmidt, Voegler-Lee, & Bryant, 2011) and show different patterns of relations with other measures, such as verbal mental age (e.g., Hongwanishkul, Happaney, Lee, & Zelazo, 2005), academic achievement (e.g., Brock et al., 2009; Willoughby et al., 2011), theory of mind (e.g., Carlson et al., 2002), and behavior problems (e.g., Thorell, 2007; Willoughby et al., 2011). Other research, however, has failed to find evidence for hot and cool factors (e.g., Allan & Lonigan, 2011; Sulik et al., 2010), suggesting instead that EF may correspond to a unitary construct in early childhood. To date, however, factor analytic research on hot and cool EF has focused on children about 6 years old or younger, and it is possible that the distinction is only starting to emerge in this age range, consistent with a general process of increasing functional specialization of neural systems that initially are relatively undifferentiated but become more specialized with experience as part of a developmental process of adaptation (e.g., Johnson, 2011).

Research on cool EF shows a similar pattern: Whereas multiple factors such as cognitive flexibility and working memory are differentiated in older children (e.g., Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003) and adults (Miyake et al., 2000), research with younger children supports a single-factor construct (Wiebe, Espy, & Charack, 2008; Wiebe et al., 2011). Research comparing cool EF with a wide range of other less purely executive cognitive functions (e.g., vocabulary) also finds evidence of increasing differentiation (from two to six factors) with increasing age (Zelazo et al., in press).

PLASTICITY OF EF

Although longitudinal research suggests that individual differences in both hot and cool EF show considerable stability across time (e.g., Casey et al., 2011; Polderman et al., 2007), the reasons for this stability remain unclear. One likely possibility is that key aspects of children's environments tend to remain stable, and there is now evidence that EF is associated with the contexts in which children develop, including, for example, their SES and their attachment relationships (see Carlson et al., in press, for a review). At the same time, however, the human brain is an inherently plastic organ, continually adapting to its environment. Indeed, research on various neural systems (e.g., sensory systems) suggests that there are periods of relative plasticity (often called "sensitive periods") when particular regions of the brain and their corresponding functions are especially susceptible to environmental influences. These periods typically correspond to times of rapid growth in those regions and functions (Huttenlocher, 2002), and in contrast to earlier notions of genetically programmed "maturation" (e.g., Gesell, 1933), these periods of relative plasticity are now assumed to reflect both experience-expectant and experience-dependent processes (Greenough, Black, & Wallace, 1987).

The finding that EF develops most rapidly during the preschool years is consistent with the suggestion that this may be a period of high malleability (Carlson et al., in press)—one that occurs just as children face sharp increases in the demands placed on their EF (e.g., as they transition to school). A growing body of research has now demonstrated conclusively that EF can be cultivated through training regimes that require the use of prefrontal cortical circuits (cf. Hebb, 1949). Much of this research has focused on the preschool years (see Diamond & Lee, 2011, for a review), and research has shown not only behavioral improvements but also corresponding changes in neural function (e.g., Rueda et al., 2005). Preschool curricula designed to foster the development of EF have also yielded promising results (Diamond, Barnett, Thomas, & Munro, 2007; Lillard & Else-Quest, 2006), and the beneficial effects of other early childhood programs that promote competence and academic success may be associated with, and even mediated by, concomitant improvements in EF (Riggs, Greenberg, Kusche, & Pentz, 2006).

Although the preschool years may be an especially sensitive period for EF, there is also considerable reorganization of prefrontal systems during the transition to adolescence, when gray matter volume in prefrontal cortex reaches a peak (Giedd et al., 1999). This reorganization is likely to be sensitive not only to events in the internal environment (e.g., a shift in dopamine receptors from mesolimbic toward mesocortical systems; Spear, 2000) but also to events in the external environment, and as can be seen in Figure 1, it is associated with another increase in the rate at which EF develops. Indeed, several studies have found that EF can also be trained in older children and adolescents (e.g., Duckworth, Grant, Loew, Oettingen, & Gollwitzer, in press; Jaeggi, Buschkuehl, Jonides, & Shah, 2011). One example of a successful intervention with adolescents and adults is CogMed, designed to train working memory. Klingberg et al. (2005) found that after 5 weeks of training, a group of 7- to 12-year-olds with attention deficit hyperactivity disorder (ADHD) showed improved working memory and reduced ADHD symptomatology. In a study of CogMed with adults, Olesen, Westerberg, and Klingberg (2003) found training-related increases in activity in frontal and parietal areas, as well as decreases in activity in cingulate cortex.

CONCLUSION: OPPORTUNITIES FOR EARLY INTERVENTION AND PREVENTION

Impairments in EF are prominent features of various clinical conditions, such as ADHD and other externalizing problems (e.g., Barkley, 1997), which have their origins in early childhood and peak during adolescence. Although individual differences in EF appear to be relatively stable across the lifespan, there is also evidence that EF can be improved by practice, with corresponding changes in neural function. This combination of stability and plasticity underscores the potential value of promoting the healthy development of EF, providing lasting opportunities for what Bacon referred to as "second cogitations" to become second nature. The preschool years may be a particularly valuable window for intervention: They appear to be marked by considerable plasticity, and a boost in EF just prior to the onset of school may initiate a cascade of beneficial events for children (e.g., increasing their motivation to learn, helping them establishing good relationships with teachers, reducing their problem behaviors, and allowing them to learn in a more proactive and reflective fashion). It is also clear, however, that EF can be improved by practice beyond the preschool years, and indeed, the transition to adolescence may be another period of relative plasticity. Research on hot EF and how best to foster its healthy development may be of particular practical importance during this transition, helping children to face what can be a daunting set of new emotional and interpersonal challenges.

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