CHAPTER

24

Executive Function

Development, Individual Differences, and Clinical Insights

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OUTLINE

24.1 INTRODUCTION

Executive function (EF) is an umbrella term that encompasses the set of higher-order processes (such as inhibitory control, working memory, and attentional flexibility) that govern goal-directed action and adaptive responses to novel, complex, or ambiguous situations (Hughes et al., 2005). Research into the neural substrate for EF (Golden, 1981) has long focused on the prefrontal cortex (PFC), but this traditional view recently has been challenged for two reasons. First, positron emission tomography studies demonstrate that EF tasks activate parietal areas involved in basic attentional processes more strongly than the PFC (for a review, see Jurado and Rosselli, 2007); similar findings also have been reported in a recent magnetic resonance imaging (MRI) study of EF in children and adolescents (Tamnes et al., 2010). Second, clinical studies show that early pathology in any brain region leads to executive deficits, such that, for children at least, intact EF depends upon the integrity of the entire brain, not just the frontal regions (Anderson and Catroppa, 2005).

Research into EF in children has grown exponentially over the past few decades. A recent Scopus search using the terms *executive functions* and *children* showed just 5 studies prior to 1980; 26 studies between 1980 and 1990; 216 studies between 1990 and 2000; and 1092 studies between 2000 and 2010. This massive expansion of research reflects the growth of interest in childhood clinical groups, and EF deficits are apparent in a number of different developmental disorders – especially attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder (ASD) (Pennington and Ozonoff, 1996; Sergeant et al., 2002). However, recent years also have seen a rapid growth in studies of normative age-related changes in EF and its neural substrates, enabling a valuable crossover between research on typical and atypical development. As Tau and Peterson (2010, p. 162) put it, documenting normative pathways of brain development "provides the Archimedean point from which to interpret and understand the aberrant pathways of brain development that produce disease," whereas studying atypical groups "informs our knowledge of normal brain

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development by throwing into relief the developmental pathways that are most sensitive to perturbation."

Both the pervasiveness of EF deficits in childhood disorders and the salience of EF for studies of normal brain development can be understood in terms of the protracted nature of EF development. Thus, EF skills begin to emerge in infancy (Diamond, 1988), show marked improvements across toddlerhood and the preschool period (Carlson et al., 2004; Hughes and Ensor, 2007; Hughes et al., 2010), and continue to improve during the school-age years (e.g., Huizinga et al., 2006), with some aspects of EF continuing to develop throughout adolescence (Luciana et al., 2005; Luna et al., 2004). Interestingly, although several reviews of EF development are available (e.g., Anderson, 2002; Best et al., 2009; Blair et al., 2005; Blakemore and Choudhury, 2006; Garon et al., 2008; Hughes and Graham, 2002), few span the full period of development (for an exception, see Diamond, 2002). To address this gap, the first section of this chapter provides a synopsis of research findings on developmental trajectories for EF from infancy to adolescence in both typical and atypical populations.

Having a protracted developmental course also makes EF a focus of interest for researchers interested in exploring environmental influences. As noted by Garon (2008) and Hughes and Ensor (2009), this topic of environmental influence on EF is a promising new direction for research because the slow maturation of the frontal cortex and its networks makes it heavily dependent on the environment (e.g., Noble et al., 2005). However, until recently, the processes underpinning environmental influences on EF have been, in research terms, largely *terra incognita*. To rectify this gap, the second section of this chapter provides an overview of three strands of recent research that investigate (1) effects of training or intervention programs on children's emerging EF skills, (2) influences of parent–child interactions on EF, and (3) studies of environmental influence on EF in clinical groups.

Interwoven with perspectives on EF that emphasize typical or atypical development, the expansion of research in this field also mirrors the intensity of research into children's understanding of mind; numerous studies have reported a robust association between EF and children's theory-of-mind skills that is evident across a broad age range, independent of covariant effects of language ability and intelligence quotient, and applies to both typical and atypical populations. In addition, recent research has demonstrated that early emerging skills in both EF and theory of mind are strong predictors of children's readiness for school and their performance in academic subjects. The third section of this chapter aims to bring together the findings from research, tracing links between EF and children's academic, sociocognitive, and social success at school.

24.2 NORMATIVE DEVELOPMENTAL TRAJECTORIES FOR EF FROM INFANCY TO ADOLESCENCE

The past two decades have seen a massive increase in the availability of child-friendly EF tasks (for a useful summary, see Garon et al., 2008), leading to dramatic improvements in the understanding of the development of EF. For instance, it is now known that EF is a unitary construct with partially dissociable components (Garon et al., 2008) that begins to emerge in the first few years of life (e.g., Diamond, 1991) and continues to develop through to adulthood (Huizinga et al., 2006). However, most studies in this field have been cross-sectional in design and have not controlled for peripheral task demands. As a result, both cohort effects and developmental changes in how children cope with peripheral task demands may contribute to age-related contrasts in EF performance. In addition, simplifying adult tasks to make them age-appropriate for young children carries the danger of losing the critical EF component (Garon et al., 2008). These notes of caution need to be remembered when considering the summary review of findings from infants to adolescents given below.

24.2.1 Infancy

The first evidence that EF emerges in the first year of life (much earlier than previously believed) came from studies using Piaget's object permanence task in which babies are repeatedly allowed to retrieve an attractive object from one location (A) before seeing it hidden at a new location (B). Early studies indicated that while 8-month-olds and older babies typically search correctly at location B, 5-month-olds persist in searching for the object at location A (e.g., Harris, 1975). Although Piaget interpreted this 'A not B' error as a failure to recognize that objects have an independent existence in the world (i.e., a lack of 'object permanence'), later studies showed that when looking times rather than physical reaches are used to assess perceptual understanding, even 4-month-olds do well (e.g., Baillargeon et al., 1985). Thus, young babies who make the A not B error in their reaching responses may know that the object has been moved, but fail to inhibit their previously successful (and therefore prepotent) reach to A. Thus, success on this task can be seen as reflecting infants' growing cognitive flexibility and volitional control (Diamond and Goldman-Rakic, 1989). Other tasks that also demonstrate early executive skills in infancy include a detour-reaching task, in which infants are invited to retrieve an object that is visible behind a Perspex screen; success on this task depends on making a 'detour reach' around the side of the screen (Diamond et al., 1989). In short, a rudimentary ability to inhibit prepotent responses is clearly evident by 7–12 months (Diamond, 2002).

More recent studies of infants also indicate an early emergence of other aspects of EF. In particular, building on the finding by Rothbart et al. (2003) that 2-year-olds' anticipatory looking (i.e., looking to the location of a target prior to its appearance) is associated with parental ratings of self-regulation, Sheese and colleagues (2008) have reported that 6- and 7-month-olds who display high levels of anticipatory looking also show more signs of self-regulation in their approach toward novel toys. Together, these two studies indicate that executive attention (indexed by anticipatory looking) is also evident very early in life. Interestingly, Sheese et al. (2008) found that anticipatory looking was also associated with looking away from disturbing stimuli (facemasks), supporting proposals (e.g., Aksan and Kochanska, 2004; Rothbart et al., 2000) for a link between early systems of emotional control (e.g., fear and caution) and later systems of cognitive control.

24.2.2 Preschoolers

Research into the preschool years accounts for the lion's share of studies of EF in childhood. As will be discussed in the third section of this chapter, this focus on preschoolers partly reflects the intensity of research into children's understanding of mind, which shows dramatic improvements in the preschool years (e.g., Wellman et al., 2001). Another reason for a research focus on preschoolers is that a wide variety of age-appropriate tasks have been developed in response to the previous dearth of tasks suitable for young children (e.g., Carlson, 2005; Diamond et al., 1997; Espy et al., 1999; Hughes, 1998; Zelazo and Muller, 2002).

However, even when these conceptual and methodological factors are taken into account, the growth of research on preschool EF remains remarkable and is difficult to summarize briefly. Fortunately, a recent comprehensive review by Garon et al. (2008) is helpful in at least three respects. First, adopting the 'unity and diversity' model proposed by Miyake and colleagues (2000) to account for the coherent yet fractionated nature of EF in adults, Garon et al. (2008) demonstrate that the three key components of EF (working memory, response inhibition, and set shifting) in adults are all evident before the age of 3 years. Second, Garon et al. (2008) address the question of how developmental changes in EF across the preschool years should be characterized, and, consistent with proposals from other theorists (e.g., Rothbart and Posner, 2005), highlight the importance of age-related improvements in attention and coordination of distinct EF components. As they observe, attention also appears central to theoretical accounts that characterize EF development in terms of increased ability to overcome prepotent thoughts/acts (Diamond, 2002) or latent representations (Munakata, 2001) or to integrate conflicting rules (Zelazo et al., 2003).

Third, Garon et al. (2008) offer a number of suggestions for future research. One suggested direction (discussed more fully in the next section of this chapter) concerns the importance of studying environmental influences, as the slow maturation of the PFC and its networks make it heavily dependent on the environment (Noble et al., 2005). Another suggested direction is the use of longitudinal designs in order to examine developmental changes in EF. This is an important point as research into preschool EF (like so many fields within developmental psychology) is heavily dominated by cross-sectional studies that do not allow researchers to control for individual differences. In one exceptional longitudinal study, Hughes et al. (2010) applied latent-variable analyses to demonstrate that: (1) latent factors for EF in preschool and early school age show measurement invariance (supporting the validity of across-time comparisons of average EF performance); (2) individual differences in the preschool latent factor for EF are positively related to both maternal education and early verbal ability; and (3) rates of growth in EF are inversely related to verbal ability (such that preschoolers with low verbal ability begin to catch up with their peers following the transition to school) but are unrelated to maternal education (i.e., there is no independent catch-up effect for children with less-educated mothers). As these findings illustrate, adopting longitudinal study designs to examine developmental trajectories in early EF is valuable, both theoretically and for the development of educational policy.

24.2.3 School Age

Studies of EF in school-aged children often involve computerized tasks, which allow researchers to standardize administration, to include large numbers of trials, and to collect information on reaction times. One widely used battery of computerized EF tasks is the CANTAB (CAmbridge Neuropsychological Tests – Automated Battery), which was developed for work with adult clinical groups (Luciana, 2003) and was first administered to children in the Hughes et al. (1994) study of children with ASD; subsequent studies have confirmed that the CANTAB is sensitive to EF deficits in ASD across a wide range of ages and ability levels (Ozonoff et al., 2004). Normative data on age-related improvements in EF in typically developing children (screened to exclude children with learning or behavioral difficulties) have also been gathered (Luciana, 2003).

A key finding to emerge from studies of EF across the school years is that step-wise improvements are evident at different ages for different aspects of EF. Specifically (as noted earlier), the preschool years are characterized by dramatic improvements in inhibitory control, but studies of young school-aged children highlight improvements in cognitive flexibility and studies of preadolescents emphasize improvements in working memory and planning ability. For example, using the intradimensional/extradimensional (IDED) shift task from the CANTAB battery, Luciana (2003) reported a marked improvement in children's ability to shift their mental set around the age of 6 or 7 years. The IDED task is a multistage task that is based on the Wisconsin Card Sorting Task, which requires participants to work out a rule for sorting cards (e.g., sort by color, number, or shape of stimuli) and, then, when they receive negative feedback indicating that the rule has changed, to shift strategy in order to sort by a new rule. In the same study, Luciana (2003) showed that clear improvements on the Tower of London planning task or on a self-ordered search test of working memory were often not evident before the age of 11 or 12 years. Other studies using different tasks have reported a similar contrast in the developmental trajectories of different aspects of EF. For example, several studies report improvements in mental flexibility around age 8 years (e.g., Anderson, 2002; Anderson et al., 2001c), while planning, organizing, and strategic thinking are typically reported to emerge later and to show age-related improvements throughout adolescence (Anderson et al., 1996, 2001a; De Luca et al., 2003; Krikorian et al., 1994; Welsh et al., 1991).

At odds with this general pattern, however, are findings from another study that suggest a long developmental progression for cognitive flexibility, with 13-year-olds still not at adult levels (Davidson et al., 2006). A closer look at the specific tasks suggests that the contrast in these findings may be explained by Diamond's (2009) 'all or none' theory. According to this theory, the brain and mind work effortlessly (or under difficult conditions) at a gross level, but require effort (or more optimal conditions) to work in a more selective manner. Thus, it is easier to inhibit a dominant response all the time than only some of the time. As a result, even older children are likely to show frequent errors on task-switching paradigms, such as those used in the Davidson et al. (2006) study. This study also revealed several other interesting developmental contrasts. For example, adults slowed down on difficult trials to preserve accuracy, but children (and especially young children) were impulsive and so made errors on difficult trials. These contrasting speed accuracy trade-offs highlight the value of using computerized tasks to assess EF. At the same time, these advantages may be offset by a reduction in sensitivity. For example, children with ASD have been found to perform significantly better on a computerized set-shifting task than on a manual version (Ozonoff, 1995). In addition, computerized tasks are likely to have lower ecological validity, such that there is still a need for manual tasks that mimic everyday EF demands. Here, one task battery that deserves mention is the behavioral assessment of dysexecutive syndrome (Norris and Tate, 2000), which includes tasks that tap into abilities for multitasking, problem solving, and strategic thinking.

24.2.4 Adolescence

Consistent with the findings from younger samples described above, different aspects of EF have been reported to show distinct trajectories across the adolescent years. For example, in a study of Australian 11- to 17-year-olds that included a variety of EF tasks, Anderson et al. (2001b) found clear linear age-related improvements on tests of selective attention, working memory, and problem solving, but no age-related difference in planning performance.

Also echoing findings from studies of younger samples is an emerging theme from the adolescent literature regarding the importance of considering EF alongside other key brain systems. For example, Tau and Peterson (2010) note that adolescents and adults differ not just in the maturity of their EF functions, but also in the extent to which they avoid risk and respond to reward/peer influence (adolescents are less risk-averse, more driven by reward and more easily influenced by peers). As a result, accounts of developmental change in everyday behavior should consider not only top-down EF systems but also bottom-up motivational and emotional responses to situations of risk and reward.

Similar conclusions emerge from a recent community-based study of relations between EF, problem behaviors, and risk taking in 10- to 12-year-olds (Romer et al., 2009). In this study, the children's self-reported impulsivity was inversely related to both working memory and reversal learning and explained individual differences in both externalizing problems and performance on a risk-taking task. Noting that interventions to improve children's working memory have led to reductions in impulsive behaviors (e.g., Klingberg et al., 2005), the authors of this study concluded that young people who have difficulties in considering multiple (and potentially conflicting) goals will be less likely to either 'look before they leap' or temper their interest in novel or exciting experiences.

24.3 CLINICAL INSIGHTS, FROM INFANCY TO ADOLESCENCE

In parallel with, and perhaps fueling the growth of, research on normative development in EF, studies of EF in atypical child populations have grown dramatically and yielded several interesting findings that together emphasize the extent to which EF can be impaired by brain abnormalities or insults, especially if these occur early in life.

24.3.1 Infancy

The first clinical study of EF in infancy highlighted the importance of dopamine for EF. Specifically, Diamond et al. (1997) conducted a 4-year longitudinal study of children treated early and continuously for phenylketonuria (PKU), a metabolic disorder characterized by a failure to convert phenylalanine to tyrosine (the precursor of dopamine) that, if untreated, is the most common biochemical cause of intellectual disability. On tests of working memory and inhibitory control, children with PKU with high plasma levels of phenylalanine performed more poorly than all other control groups (including siblings and PKU children with lower levels of phenylalanine). Moreover, this impairment was specific to performance on EF tasks, directly related to levels of phenylalanine, and evident across the age groups, from the youngest (6–12 months) to the oldest (3½–7 years).

Long-term deficits in EF are also found in infants born prematurely and infants exposed prenatally to high levels of alcohol. In a recent meta-analysis, Mulder et al. (2009) showed that children born prematurely displayed a variety of EF impairments, with the degree of impairment predicted by: (1) gestational age (i.e., extremely premature infants show greater deficits), (2) age at test (group differences attenuate with age), and (3) aspect of EF under test (this 'catch-up' effect is evident for selective attention skills but not for attentional set-shifting skills). No corresponding systematic review of EF in children with prenatal alcohol exposure is yet available, but individual studies consistently report deficits in EF that are independent of IQ (e.g., Connor et al., 2000; Green et al., 2009; Mattson et al., 1999; Schonfeld et al., 2001) and somewhat distinct from EF deficits in other groups, such as children with ADHD (e.g., Vaurio et al., 2008). Moreover, a recent friendship training study involving primary-school-aged children with prenatal alcohol exposure showed that parental ratings of EF predicted gains in social skills, even when effects of IQ were taken into account (Schonfeld et al., 2009). In short, prenatal alcohol exposure has long-term adverse effects on children's emerging EF skills, which in turn not only underpin academic achievement (see later in this chapter) but also play a key role in these children's social competencies.

24.3.2 Preschoolers

From a clinical perspective, preschool milestones in EF have attracted considerable attention from researchers studying the cognitive profiles associated with ASD. For example, Hughes and Russell (1993) demonstrated that children with ASD (with a verbal mental age of at least 4 years) displayed significant difficulties on two tasks that most 4-year-olds passed with ease. The first of these was the 'Windows' task in which, for each of 20 trials, children could win a treat (visible through a window in a box) by choosing a visibly empty box. Children with ASD (and many 3-year-olds) chose the baited box, and often persisted in this incorrect response across all 20 trials. Moreover, administering the task in four different conditions (verbal/nonverbal; competitor present/absent) led to no change in the results. In the second task, to retrieve a large and attractive marble from inside a metal box, children needed to perform a simple but arbitrary means–end action (flicking a switch at the side of the box that turned off a simple circuit with an infrared beam that, if tripped, activated a small trapdoor on which the marble was resting). Once again, most older children with ASD and typically developing 3-year-olds (but not 4-year-olds) persisted in making a direct and unsuccessful attempt to reach into the box.

These findings added weight to reports of impaired performance by children with ASD on more traditional (and complex) EF tasks (e.g., Hughes et al., 1994; Ozonoff et al., 1991; Prior, 1979) and sparked a sustained program of research on EF deficits in ASD (for reviews, see Hill, 2004; Pennington and Ozonoff, 1996). The breadth and sophistication of current research in this field are nicely illustrated by a handful of recent findings that include: (1) evidence for associations between impaired inhibitory control and high-level repetitive behaviors (e.g., compulsions and preoccupations) in children with ASD (Mosconi et al., 2009); (2) imaging results that indicate reduced functional connectivity and network integration between the frontal, parietal, and occipital regions among individuals with ASD in completing EF tasks (Solomon et al., 2009); (3) longitudinal evidence for the importance of early EF in shaping the developmental trajectory of theory-of-mind skills in children with ASD (Pellicano, 2010); and (4) evidence for age-related improvements in EF from childhood to adolescence in ASD, indicating the presence of plasticity and suggesting a prolonged window for effective treatment (for a review, see O'Hearn et al., 2008).

24.3.3 School Age

Earlier, in the section on EF in typically developing school-aged children, concern was raised about the ecological validity of the computerized tasks that are often used with this age group. This issue of ecological validity is also salient from a clinical perspective, as EF deficits in children with ADHD (who, by definition, show marked problems of impulsivity/inattention/disorganization in their everyday lives) are often less pervasive and severe than the EF deficits shown by children with ASD (e.g., Geurts et al., 2004; Goldberg et al., 2005; but see also Happé et al., 2006), such that contemporary causal accounts of ADHD also include additional deficits in the signaling of delayed rewards (e.g., Sonuga-Barke, 2005).

In his review, Sonuga-Barke (2005) also argues for the importance of considering EF deficits alongside environmental influences, a view that is supported by the peak in diagnosis for ADHD at age 12 (Mandell et al., 2005); that is, just following the transition to secondary (or 'middle') school, which brings a significant increase in demands for self-controlled and planful behavior. Indeed, a recent longitudinal study that modeled trajectories for parent-rated ADHD symptoms confirms that the age-related decline in symptoms is at least transiently reversed following the transition to secondary school (Langberg et al., 2008). Likewise, in a study that involved carefully matched samples, Happé et al. (2006) found that children with ASD, but not children with ADHD, showed age-related improvements in EF performance. Together, these findings highlight the importance of adopting a developmental perspective when examining EF deficits in atypical groups.

24.3.4 Adolescence

Much of the clinical work on EF in adolescence has concerned risk taking and substance abuse. In particular, several researchers have reported a robust predictive association between poor EF and impulsivity in preadolescence and high levels of drug use in late adolescence (e.g., Aytaclar et al., 1999). Similarly, in a review of alcohol addiction in adolescence, Wiers et al. (2007) proposed a model in which repeated alcohol use leads to compromised EF development coupled with sensitization of a reward-based approach system. Note that this model adopts Tau and Peterson's (2010) recommended dual focus on top-down and bottom-up processes.

In the dual-focus study by Fairchild et al. (2009), there is a comparison between how adolescent boys with early- versus late-onset conduct disorder (CD) or controls perform on tests of EF (Wisconsin Card Sort Test) and decision making (Risky Choice task) under conditions of varying motivation and stress. Controlling for effects of IQ, they found nonsignificant group differences in EF, but more risky choices in both CD groups than in controls; adolescent boys with early-onset CD made risky choices even when the gains were relatively small. These findings suggest a shift in the balance between sensitivity to reward and punishment among boys with CD (particularly the early-onset form) that is similar to the imbalance proposed by Wiers et al. (2007) in top-down and bottom-up processes in addictive adolescents. Perhaps unsurprisingly then, CD is, as Fairchild et al. (2009) note, associated with a significantly increased susceptibility to substance-use disorders.

24.4 FROM BIOLOGICAL TO ENVIRONMENTAL PREDICTORS OF INDIVIDUAL DIFFERENCES IN EF

Biological studies have been hugely influential in research on EF in childhood. For example, the impact of Diamond and colleagues' (1989) EF account of age-related improvements in infants' performance on the A not B task was greatly increased by the convergent findings from parallel studies of: (1) rhesus monkeys (Diamond et al., 1989), which highlighted the dorsolateral PFC as pivotal to success on this task, and (2) children with PKU, which demonstrated the importance of dopamine for success on a wide battery of simple EF tasks (Diamond et al., 1997). More recently, in their review of studies using functional MRI, Tau and Peterson (2010) concluded that age-related improvements in EF in childhood are associated with increased activation of (dopamine-rich) frontal and striatal circuits.

Other seminal findings include the demonstration of Golden (1981) that myelination of the prefrontal cortex is associated with age-related improvements in EF in children. More recent technological advances have led to significant progress in documenting parallels between milestones in EF development and changes in brain myelination (e.g., Nagy et al., 2004). This progress is particularly evident in Giedd et al.'s (1999) large-scale longitudinal MRI work on adolescence, which has shown that this period is characterized by both a linear increase in white matter and a nonlinear decrease in gray matter. Gains in white matter have clear functional consequences, which include faster and more efficient sharing of information within the frontostriatal circuits and smoother communication between the frontal cortex and other brain regions (Paus, 2010). Peak periods of reduction in gray matter occur just after puberty and at the transition from adolescence to adulthood; although typically attributed to synaptic pruning, this 'loss' of gray matter may simply reflect gains in white matter (Paus, 2010). As noted in a recent review (Blakemore and Choudhury, 2006), structural changes in the adolescent brain are particularly evident in the frontal cortex and are linked to age-related improvements in inhibitory control (Luna et al., 2004), working memory (e.g., Luciana et al., 2005), and decision making (e.g., Hooper et al., 2004).

The studies of EF in atypical groups summarized in the previous section provide a third strand of research with a clear biological perspective. In particular, impairments in EF are most pronounced among children with ADHD or ASD (Pennington and Ozonoff, 1996), two disorders that show substantial genetic influence (Kuntsi et al., 2004; Ronald et al., 2006). Indeed, EF has recently been implicated in the genetic basis for ADHD (e.g., Bidwell et al., 2007; Gau and Shang, 2010). More direct evidence for strong genetic influences on early EF comes from studies that include genotyping (e.g., Fossella et al., 2002; Rueda et al., 2005), which demonstrate that children with the homozygous long allele for the DAT1 gene (associated with high effortful control and low extroversion) outperform those with the heterozygous (long/short) allele on EF tests of conflict resolution (for a recent review of molecular genetic studies of EF in children, see Brocki et al., 2009).

However, none of the above findings precludes environmental factors also contributing to either developmental change or individual differences in EF. Indeed, genetic factors often show substantial interactions with environmental influences, such that genetic vulnerability is expressed only among individuals exposed to environmental stressors, such as harsh parenting or family chaos (Asbury et al., 2003, 2005). Moreover, as noted earlier, the development of EF has a very protracted course, which makes it particularly sensitive to environmental influence (Farah et al., 2006; Noble et al., 2005). In addition, current cognitive models of EF (e.g., Duncan, 2001) highlight the fluidity of relations between the prefrontal cortex and EF performance. Specifically, neurons within the PFC show a rapid adaptation to changing task demands (Freedman et al., 2001), making it difficult to map between behavioral and neuronal functions. In comparison with research on biological influences, studies of environmental influences on EF are largely *terra incognita*. Nevertheless, there is growing recognition that early experiences contribute to children's neurocognitive development. Specifically, unfavorable early environmental experiences adversely affect both brain structure (e.g., De Bellis, 2005) and function (e.g., Rutter and O'Connor, 2004); conversely, positive experiences (especially with caregivers) appear to have a positive impact on brain development (e.g., Nelson and Bloom, 1997; Schore, 2001). As Bierman et al. (2008, p. 823) put it, 'EF development depends, in part, upon sensitive responsive caregiving and opportunities for guided exploration of the social and physical environment, fostering sustained joint attention, emotional understanding, planning, and problem solving.'

Direct evidence for environmental effects on EF comes from intervention studies, which can be considered in two sets. The first set of studies involves direct training on task analogs. In the first of these studies, Kloo and Perner (2003) gave a simplified version of the Wisconsin Card Sort task to typically developing preschoolers and found that both card-sorting training and false-belief training (each delivered in two sessions on separate days) led to positive effects on EF at posttest. More recently, Rueda et al. (2005) gave 5 days of attention training to groups of 4- and 6-year-olds, and reported that children who performed poorly at pretest showed the greatest gains from this training program, with the overall improvements in executive attention and IQ performance being equivalent to half the difference between older and younger participants (i.e., to gains expected from 1 year's difference in age). Similarly, in a recent review, Klingberg (2010) reported that, across a wide variety of age groups, training leads to significant improvements in working memory. However, not all aspects of EF appear so malleable to training. For example, a 5-week preschool training program has been shown to produce significant improvements in working memory but not in inhibitory control (Thorell et al., 2009), raising interesting questions as to whether the distinct processes that underpin different aspects of EF lead to contrasts in the extent to which performance can be improved by training. The final study in this set of training interventions was conducted by Karbach and Kray (2009) and involved training on task switching, administered to both school-aged children (aged 8–10 years) and two groups of adults (aged 18–26 and 62–76 years). All three groups showed positive effects that transferred to other EF tasks and to tests of fluid intelligence (e.g., tests of abstract thinking and reasoning); however, when the training tasks were variable, improvements were reduced for children but increased for adults. This interaction effect highlights the importance of adopting a developmentally sensitive approach to the development of interventions.

The second set of intervention studies adopts a broader and more naturalistic approach and is thus perhaps of greater relevance for theories of how everyday social environments might impinge on children's EF development. At least three such interventions have been assessed using randomized control trials (RCTs). The first of these, Head Start REDI (REsearch based, Developmentally Informed), is integrated into the Head Start prekindergarten program for disadvantaged children and involves brief lessons, 'hands-on' extension activities, and specific teaching strategies linked empirically with the promotion of social–emotional competencies, language development, and emergent literacy skills. In their RCT, Bierman et al. (2008) reported that the REDI intervention led to significant improvements in children's abilities to stay on task, coupled with marginally significant gains in set-shifting performance. Another well-recognized intervention is the Vygotskian 'Tools in the Mind' preschool curriculum (Bodrova and Leong, 1996; Diamond et al., 2007), which includes a variety of specially designed activities (e.g., sociodramatic play and shared reading) that enable children to progress from external to shared to self-regulation; teachers are also trained to foster early skills in literacy and mathematics by encouraging reflective thinking and metacognition. Interestingly, although language plays a pivotal role in Vygotskian accounts of cognitive development, the Tools curriculum appears to have positive effects on EF (as indexed by low problem behavior scores), but no significant impact on language development (Barnett et al., 2008). The third RCT focused on an 8-week school-based intervention for older children (7- to 9-year-olds) that aims to promote mindful awareness practices through twice-weekly half-hour sessions. Comparing teachers' and parents' pre- and post-program ratings of EF skills, Flook et al. (2010) reported that less well-regulated children showed particularly clear treatment-related gains (evident both at school and at home); note that this finding echoes earlier results from preschoolers (e.g., Rueda et al., 2005).

Together, the findings from these three RCTs support two of the three dimensions of adult–child interactions that Carlson (2003) has proposed as likely to favor EF in children: *scaffolding* (which provides children with successful experiences of problem-based learning) and *mind-mindedness* (which provides children with verbal tools for progressing from external to internal forms of self-regulation). Positive effects on EF of the third dimension of *sensitivity* (which provides infants with successful experiences of impacting on the environment) have been reported by Bernier et al. (2010) in their recent longitudinal study of 80 infants in which maternal sensitivity, mind-mindedness, and scaffolding (or 'autonomy support') were evaluated at 12–15 months of age, and EF was assessed at 18 and 26 months. All three measures of parenting predicted child EF; however, once the effects of maternal education and general cognitive ability were taken into account, scaffolding was the strongest predictor of EF at each age. Another recent study, conducted by Bibok et al. (2009), offers a refinement of how parental scaffolding may promote young children's EF skills (indexed by performance on an attention-switching task). Specifically, observations of parents scaffolding children's goal-directed activities revealed that the *timing* of parents' elaborative utterances was a key predictor of children's attention-switching skills.

In short, there is now good evidence that parents' deliberate efforts to scaffold children's goal-directed activities do indeed foster the development of early EF skills. However, as highlighted by research on children's developing social understanding, family influences are often incidental rather than deliberate. For example, young children are extremely acute observers of family life, paying particularly close attention to injustices such as parents' differential treatment of siblings (Dunn, 1993). This point can be applied to young children's observational skills more generally; most parents will be able to recall episodes in which their actions have been mimicked with uncanny accuracy. This attention to detail favors children's rapid mastery of complex action plans: while simple mimicry of adults' planful behavior does not constitute executive control, acquiring a repertoire of 'goal-directed' acts is likely to promote EF skills. Support for this view comes from a recent longitudinal observational study by Hughes and Ensor (2009) involving a socially diverse sample of 125 children. In this study, both maternal scaffolding (in structured play with jigsaws) and opportunities for observational learning (indexed by maternal strategic behavior in a multitasking paradigm and in a shared tidy-up task) predicted improvements between the ages of 2 and 4 in children's EF scores, even when effects of verbal ability were controlled. Note that including EF assessments at both time points enabled Hughes and Ensor (2009) to take the temporal stability of individual differences in EF into account and so minimize the confounding effects of genetic factors (Kovas et al., 2007).

Reinforcing the importance of incidental effects, Hughes and Ensor (2009) also found that EF development from age 2 to age 4 was *negatively* correlated with parental ratings of disorganized and unpredictable family life, suggesting that families can hinder as well as help young children's emerging EF skills. Here it is worth noting that the social diversity of Hughes and Ensor's (2009) study sample is important: just as socioeconomic (SES) effects appear strongest at the bottom end of the scale (e.g., Scarr, 2000), adverse environmental measures (e.g., ratings of family chaos) may only show significant variance if low SES families (who are most at risk of exposure to multiple stressors) are included. Using an expanded sample from the same longitudinal study (i.e., the target children, plus friends recruited at age 4; $N = 191$), Hughes et al. (in preparation) have applied latent-variable analyses to demonstrate that each of three distinct measures of maternal well-being (specifically, depression, parental efficacy, and satisfaction) showed independent associations with individual differences in EF. Interestingly, of these three factors, only maternal depression was also (negatively) related to individual differences in children's verbal ability; that is, while positive effects of favorable family environments appear specific to EF, unfavorable family environments appear to adversely affect cognitive development in general. Note also that the significant inverse relation between maternal depression and preschool EF reported by Hughes et al. (in preparation) appears developmentally specific, as research on both older children and adolescents with depressed mothers has led to null findings (Klimes-Dougan et al., 2006; Micco et al., 2009). That said, the significant inverse relation between maternal depression and poor EF in preschoolers reported by Hughes et al. (in preparation) is supported by findings from a recent study of internationally adopted children, which demonstrate that, despite good catch-up in many specific areas of development, these young children (who were exposed to severe adverse early environments) showed persistent difficulties in EF and attentional regulation (Jacobs et al., 2010).

Clinical studies have also highlighted the importance of environmental influences. For example, studies of children who have experienced maltreatment or severe neglect highlight the impact of such extreme adverse environments on neuroendocrine and autonomic stress reactivity, which in turn leads to increased demands on EF systems of regulatory control (e.g., Bierman et al., 2008; Cicchetti, 2002). Moreover, findings from children with traumatic brain injury indicate that higher-order brain functions (such as EF) are particularly vulnerable while they are still emerging. Specifically, in their recent review of the effects of early brain injury on EF, Anderson et al. (2010) examined findings from children with focal brain pathology evident on MRI scans; they compared EF performance in late childhood/adolescence (assessed across a variety of domains) in children who sustained early brain injury at each of six developmental periods (congenital/perinatal/infancy/preschool/mid-childhood/late childhood), with these six groups being matched for gender, SES, lesion size, location, or laterality. Their findings clearly supported theoretical perspectives that emphasize vulnerability rather than plasticity in brain function. Specifically, children who experienced brain injury very early in life displayed markedly more severe deficits in EF (and IQ). In other words, while the development of EF can be disrupted, with either transient or more permanent consequences, EF skills, once established, are relatively robust (Johnson, 2005; Thomas and Johnson, 2008).

24.4.1 Early EF Predicts Academic, Sociocognitive, and Social Success at School

This third section aims to bring together the findings from research tracing links between EF and children's academic, sociocognitive, and social success at school. Interestingly, each of these research areas highlights different aspects of EF: working memory appears central in accounts of EF and academic performance; cognitive flexibility is highlighted by more than one account of EF and social cognition; and inhibitory control is central to accounts of EF and social success. At the same time, overlapping associations are likely, as there is very close interplay between children's academic ability, social understanding, and social behavior at school.

24.4.1.1 EF and Academic Performance

Over the past two decades, research into the neurocognitive underpinnings of children's competence in core academic domains such as literacy and numeracy has expanded rapidly; interestingly, several accounts give EF (especially working memory) a prominent role (e.g., Blair and Razza, 2007; Gathercole and Pickering, 2000; Geary, 1990). Empirical research confirms the importance of working memory for academic achievement. For example, in a recent longitudinal study, Alloway and Alloway (2010) found that working memory at age 5 (i.e., at the start of formal education) eclipsed IQ as a predictor of academic success 6 years later. Likewise, accounts of academic failure among children and adolescents with ADHD highlight the importance of deficits in EF (e.g., Alloway et al., 2010; Clark et al., 2000), while Dahlin (2010) found that primary school children with special needs who completed a cognitive training program designed to enhance working memory also displayed accelerated reading development. That said, the role of working memory in mathematical competence is more complex than previously thought (Geary, 2010). In particular, echoing the finding (discussed in the first section of this chapter) that developmental timing is a stronger predictor of EF impairment than location of brain injury (Anderson et al., 2010), recent studies have shown significant changes in brain–mathematics relations as children develop and mature (Ansari, 2010; Meyer et al., 2010).

Working with younger children, and adopting a rather different theoretical perspective (in which early EF rather than academic performance is center stage), Blair and colleagues have shown that individual differences in EF in preschool predict both school readiness and children's success in numeracy and literacy (Blair and Diamond, 2008; Blair and Peters, 2003; Blair and Razza, 2007; Razza and Blair, 2009). In their review of this field, Blair and Diamond (2008) argue that early self-regulation reflects an emerging balance between emotional arousal and cognitive regulation, such that self-regulation (and hence children's school readiness) is likely to be enhanced by school interventions that link emotional/motivational arousal with activities designed to promote EF.

More recently, Hughes and Ensor (in press) have extended this research field in two ways: adopting a developmentally dynamic approach to examine *growth* of EF across the transition to school and considering individual differences in EF trajectories in relation to children's own *perceptions* of their (academic and social) success at school. Research on children's self-perceived academic abilities has burgeoned over recent years, fueled by the finding that individual differences in IQ fail to account for up to 50% of the variance in academic performance (e.g., Chamorro-Premuzic and Furnham, 2005; Rhode and Thompson, 2007). Indeed, a meta-analytic review has shown that, even controlling for previous achievement, self-perceived abilities exert small but consistent effects on later achievement (Valentine et al., 2004). Conversely, poor self-perceptions in early childhood are associated with loneliness, withdrawal, and peer exclusion (Coplan et al., 2004). Together, these findings suggest that self-perceptions may be a key aspect of children's psychological (as opposed to practical) school readiness. In their study (in which 191 children were followed from ages 4 to 6), Hughes and Ensor (in press) found that, even with effects of concurrent verbal ability and EF controlled, children who had made rapid gains in EF across the transition to school reported higher levels of academic competence at age 6. Given that this is the first study to report an association between preschool EF and school-children's self-perceived abilities, it is worth noting that similar findings have been obtained from adult samples. In particular, Tangney and colleagues (2004) have reported that, among adults, individual differences in self-control (a construct that is closely related to EF) show robust associations with individual differences in self-esteem.

24.4.1.2 EF and Social Cognition

The finding that individual differences in EF trajectories predict children's self-perceived academic competence brings us to another hot topic, namely the robust association between variation in preschoolers' EF skills and in their understanding of mind. Interestingly, this link between EF and understanding of mind is evident at several different periods of development, from toddlerhood (e.g., Carlson et al., 2004; Hughes and Ensor, 2005) to adolescence (Dumontheil et al., 2010). Equally remarkable, the association between EF and theory of mind has been reported for a variety of clinical groups, including children with ASD (e.g., Pellicano, 2007), hyperactivity or conduct problems (Hughes et al., 1998), traumatic brain injuries (Dennis et al., 2009), and fetal alcohol syndrome (Rasmussen et al., 2009). Thus, the link between EF and theory of mind appears pervasive. How then should it be explained?

In an early review of the evidence for associations between EF and theory of mind, Perner and Lang (1999) offered five possible explanations: (1) *theory-of-mind skills are necessary for children to pass EF tasks* (e.g., in order to inhibit a particular response, children have to be able to represent it as maladaptive); (2) *EF is needed for children to develop their understanding of mental states* (e.g., experience of goal-directed action improves children's conceptual understanding of intentional states); (3) the relevant theory-of-mind tasks require EF (e.g., standard false-belief tasks place heavy demands on children's inhibitory control and/or working memory); (4) *tests of both EF and theory of mind require the same kind of embedded conditional reasoning*; and (5) the two systems are not functionally related, but have overlapping or neighboring *neural substrates*.

Having reviewed the evidence, Perner and Lang (1999) concluded that only a third of these proposals could be ruled out with confidence; in a subsequent study (see also Perner et al., 2002), the fourth account was also ruled out (as false-belief tasks appear as difficult as card-sorting tasks, despite requiring less complex conditional reasoning). Since then, evidence that similar brain regions are implicated in EF and theory of mind has grown (for reviews, see Perner and Aichhorn, 2008; Perner et al., 2006); thus, the fifth account (neuroanatomical proximity may well contribute to the association between the two domains) remains plausible. Indeed, very recent research demonstrates that dopamine, long recognized as pivotal to EF (e.g., see studies of PKU described in the first section of this chapter), also plays a key role in children's growing understanding of mind. For example, findings from a recent EEG study indicate that the dorsal medial PFC (which is rich in dopamine receptors and lies at the end of the mesocortical dopamine pathway) is a specific neurodevelopmental correlate of preschoolers' theory-of-mind development (Sabbagh et al., 2009). Likewise, using an archive of preschoolers' EEG recordings, Lackner et al. (2010) have reported that individual differences in eye-blink rate (an indirect but reliable measure of dopamine function) predicted theory-of-mind performance even controlling for several other related factors, including age, verbal ability, gender, and performance on a Stroop task (which taps the ability to inhibit a maladaptive response). Interestingly, as Lackner et al. (2010) note, dopamine provides a mechanism that may explain *both* neurobiological and experiential influences on theory-of-mind development. Specifically, dopamine promotes the neural plasticity needed to respond flexibly to environmental feedback by changing goals and expectations (e.g., Montague et al., 2004) and so may mediate the impact of family factors known to predict theory-of-mind development (e.g., frequencies of family conversations about mental states) (Ensor and Hughes, 2008) or of interactions with siblings (Perner et al., 1994) that depend on children's ability to reflect on (and revise) their own concepts of mind in order to accommodate new information from the environment.

Another area of progress in this research field has been the growth of longitudinal studies, including microgenetic studies (e.g., Flynn, 2006) and studies of toddlers (Carlson et al., 2004; Hughes and Ensor, 2007). One consistent finding to emerge from these studies is that early EF predicts later mental-state awareness more strongly than early mental-state awareness predicts later EF. This asymmetry in predictive relationships challenges Perner and Lang's first account (namely that theory of mind provides a foundation for EF). Instead, without going as far as stipulating that EF is, in some sense, necessary for the emergence of mental-state awareness, it seems reasonable to argue that EF improvements in the preschool years help explain how children *make use* of their early intuitive understanding of mind.

It is also worth noting that the relationship between EF and theory of mind may well be developmentally dynamic. For example, in a critique of the original theory-of-mind account of ASD (which is often diagnosed long before children are expected to pass false-belief tasks), Tager-Flusberg (2001) proposed that early-onset 'socioperceptual' skills (or intuitive mentalizing) depend on modular cognitive processes, whereas later-onset 'sociocognitive' skills (or off-line mental-state reasoning) depend on other aspects of cognition, such as language and EF. This model of dual processes (e.g., Apperly et al., 2009; de Vignemont, 2009) also goes some way to explaining why typically developing young children can show quite sophisticated mentalizing skills in their everyday interactions and yet fail experimental false-belief tasks.

Note also that other models of theory-of-mind development also suggest a developmentally dynamic relationship with EF. For example, Wellman and colleagues (Wellman and Liu, 2004) have proposed that improvements in children's understanding of mind involve a series of distinct achievements, such that different aspects of EF may be particularly important for specific milestones. Conversely, the stage-like nature of development in EF outlined in the first section of this chapter also suggests the need for a more differentiated approach. For example, in their study of children with traumatic brain injuries, Dennis et al. (2009) used path analysis to elucidate the nature of relations between EF and theory of mind and argued that their findings support models of EF in which inhibitory control serves as a foundation for other aspects of EF, in particular working memory (Barkley, 1997). Specifically, Dennis et al. (2009) found that the relationship between impaired inhibitory control and theory of mind was mediated, at least among children with traumatic brain injury, by impairments in working memory.

24.4.1.3 EF and Social Competence

For adults, there is robust evidence that deficits in EF are associated with problems of antisocial behavior: in a meta-analytic review of this literature, Morgan and Lilienfeld (2000) reported that the average EF performance of antisocial groups fell 0.62 standard deviations below that of control groups. Building on this work, Raine (2002) reviewed evidence from neuropsychological, neurological, and brain imaging studies and concluded that prefrontal structural and functional deficits are implicated in antisocial or aggressive behavior throughout the lifespan. Most recently, Beauchamp and Anderson (2010) have conducted a theoretical review of the cognitive underpinnings of children's developing social skills and noted that, within EF, attentional control (i.e., self-monitoring, response inhibition, and self-regulation) is especially critical.

In one of the earliest studies to link EF to young children's social competence (and the first to use direct observational methods), Hughes et al. (2000) found that, in a socially diverse sample of preschoolers (half of whom had been rated by parents as 'hard to manage'), poor performance on a battery of EF tasks (but not on theory-of-mind tasks) was associated with higher frequencies of anger and antisocial behavior toward friends. In other words, the interpersonal problems of these hard-to-manage preschoolers appear not to reflect difficulties in social understanding *per se*, but rather failure of behavioral regulation. In a follow-up study with the same sample, Hughes et al. (2001) showed that poor EF at age 4 predicted negative behavior at age 5 and that this group of hard-to-manage children continued to show rule violations and perseverative errors at age 7 (Brophy et al., 2002).

In a further longitudinal observational study (for more details, see Hughes, 2011), Hughes and colleagues followed a socially diverse sample of 140 children from toddlerhood through to school age, recruiting best friends for each target child at age 4, such that their findings are best presented in two parts. In the first, Hughes and Ensor (2008) examined children's EF, verbal ability, and theory-of-mind scores at ages 2, 3, and 4 in relation to aggregate (multi-informant and multi-setting) measures of problem behaviors at each time point and made the following findings: (1) poor EF at age 2 predicted worsening problem behaviors from ages 2 to 4; (2) individual differences in EF at age 3 fully mediated the influence of age 2 language deficits upon age 4 problem behaviors; and (3) by age 4, individual differences in problem behaviors showed specific associations with individual differences in EF (but not theory of mind or verbal ability). Capitalizing on the expanded sample ($N = 191$), Hughes and Ensor applied latent growth models, which showed that high EF gains across the transition to school predicted low levels of teacher-rated emotional symptoms, hyperactivity, conduct problems, and peer problems at age 6 (as well as higher self-reported academic competence, as noted earlier). Together, these findings highlight the importance of preschool EF for early social adjustment and demonstrate the value of examining developmental change in EF (gains in EF across the transition to school predicted social outcomes even when individual differences in concurrent EF were controlled).

Links between EF and social competence may also be indirect. For example, Razza and Blair (2009) have reported that false-belief understanding mediates the association between early individual differences in children's EF and later teacher ratings of children's social competence. On a related note, Maszk et al. (1999) found that 4- to 6-year-olds rated by peers and teachers as high in behavioral and emotional self-control became increasingly popular over the school year and so argued that individual differences in self-control may be meaningful for how children are viewed by others and hence for how they view themselves. This raises the interesting possibility with regard to Hughes and Ensor's findings. Specifically, children's awareness of their own gains in EF across the transition to school may shape both social behavior and self-concepts. If so, interventions to improve children's social adjustment might aim beyond increasing children's EF to ensuring that children are aware of their own progress in regulating and organizing their thoughts and behaviors.

At this point, it is worth noting that the findings reviewed in this chapter and elsewhere suggest that EF can act as a moderator, mediator, and outcome of interventions. For example, studies of both school-aged children (e.g., Flook et al., 2010) and preschoolers (e.g., Rueda et al., 2005) indicate that the effects of interventions are often particularly impressive for children with poor EF. Likewise, improvements in children's inhibitory control have been shown to at least partially mediate the positive effects of the PATHS curriculum on children's behavior (Riggs et al., 2006). Similarly, the three RCTs reviewed earlier in this chapter all demonstrated that positive effects on EF can be expected from enriched and structured curricula that promote scaffolding (and hence lead to experiences of successful problem-based learning) and adult mind-mindedness (enabling a progression from external to internal forms of self-regulation). These multiple roles for EF in interventions to promote social behavior highlight the importance of adopting a broad and contextualized approach to identifying underlying mechanisms. The next step is to place research on interventions within a developmental perspective to identify whether different processes are pivotal for different age groups.

24.5 CONCLUSIONS

This chapter on EF in childhood has covered considerable ground, including development from infancy to adolescence in typically developing and atypical groups; positive and negative effects of environmental influences (from training on specific tasks to exposure to enriched and predictable environments); and academic, sociocognitive, and social outcomes associated with individual differences in early EF (or EF trajectories). Perhaps the main pair of conclusions to emerge from this review is that both continuities and contrasts in EF in children of different ages are striking. One striking commonality across studies of typically developing children of different ages is a close interplay between top-down systems of EF and bottom-up reward-oriented systems, such that, from infancy through to adolescence, poor EF appears associated with risk taking and sensation seeking. Indeed, research on several atypical groups, including children with ADHD, CD, or problems of substance abuse, also highlights this interplay between top-down and bottom-up processes. Although not yet evident in research on ASD, it is worth noting that the amygdala, which is a key substrate involved in reward processing, is central to at least one prominent account of ASD (Baron-Cohen et al., 2000). Thus, extending this dual focus on EF and reward processing to children with ASD would appear a fruitful direction for future research.

A second notable developmental continuity is that, across a wide age range, typically developing individuals with good EF are more likely than their peers to do well on tests of theory of mind and show positive self-concepts and less likely to display antisocial behaviors. Perhaps related to these stable correlates of EF, longitudinal studies support EF as a predictor of later academic achievement in both young children and adolescents. Finally, across a wide variety of ages, at least some aspects of EF (e.g., working memory) appear malleable to training effects.

Examples of age-related contrasts include differences in the nature of EF: improvements in some aspects of EF (such as inhibitory control) can be seen from a very early age, while other aspects (e.g., planning) do not show marked improvements until much later on in development. Another important contrast concerns the extent to which EF can be associated with a localized neural base: age-related improvements in EF appear hand in hand with an increase in frontostriatal activation, such that development is characterized by a progression from diffuse to specific neural substrate. Several age-related functional changes in children's performance on EF tasks suggest that this progressive localization of neural substrate may reflect increases in how strategic children and adolescents are when completing EF tasks. For example, adults and children differ markedly in how they respond to more challenging situations; while adults can reduce their speed of response to remain accurate, young children typically show a drop in accuracy. Similarly, young children are particularly likely to show an 'all or none' effect, in that they can inhibit a response if this is consistently required of them, but find it much harder to cope with situations that place varying demands on this system of inhibitory control. Finally, related to these contrasts in strategy use, training studies indicate an age-related contrast in the optimal format of the training tasks, with task variability increasing training benefits in adults but reducing training benefits in children.

Together, the above age-related contrasts lead to a third key conclusion, namely the need to take developmental issues seriously when examining a construct such as EF that shows such a protracted developmental course. For example, if the differences noted above do indeed reflect an age-related contrast in strategy use on EF tasks, then the validity of across-age comparisons is in question, as different sets of skills may well underpin performance on the same task for children of different ages. An important first step in addressing this issue is to establish measurement invariance before comparing EF skills across different age groups (cf. Hughes et al., 2010). Developmental issues are also raised by findings from studies of atypical groups. Thus, studies comparing different clinical groups (e.g., children with ASD and children with ADHD) should be designed so that contrasts in developmental *trajectories* can be elucidated. The few existing studies that adopt a developmental perspective indicate that children with ASD may show greater progress than children with ADHD, but the reasons for this are not yet known.

The final conclusions to emerge from this review concern the interplay between EF and children's environments. First, although individual differences in EF have been viewed as almost entirely genetic in origin (e.g., Friedman et al., 2008), there is growing evidence that, for young children at least, environmental influences can be substantial. Thus, detailed longitudinal studies highlight the importance of family factors (e.g., maternal well-being, sensitivity, and consistency of parenting). In addition, at least three RCTs show that early educational interventions have positive effects on EF. These positive effects may be: (1) strongest for children with low levels of EF (i.e., EF moderates the impact of interventions); (2) pivotal to explaining the substantial improvement in children's behavior as a result of such interventions (i.e., EF is a mediator of intervention effects); and (3) achieved indirectly via improvements in children's theory-of-mind skills, or in how children are viewed by others, or how they view themselves. Clearly then, tracing out the mechanisms that underpin associations between family environments and children's growing EF skills as well as between interventions and children's social and cognitive achievements is an important challenge for future research.

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