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Abstract:	<p>This review of 20 years of developmental research on Executive Functions (EF) offers a broad-brushstroke picture that touches on multiple issues including: (i) findings from typical and atypical groups, from infancy to adolescence; (ii) advances in assessment tools and in statistical analysis; (iii) the interplay between EF and other cognitive systems (e.g., those involved in children’s developing understanding of mind, and in their processing of reward signals); (iv) integration of cognitive and neuroscience perspectives on EF; and (v) environmental factors that have either a positive influence (e.g., training/intervention programmes; parental scaffolding) or a negative influence (e.g., maltreatment, neglect, traumatic brain injury) on EF. Of the several themes to emerge from this review, two are particularly important; these concern the need to adopt developmental perspectives and the potential importance for intervention work of research on social influences on EF. Specifically, the review highlights both developmental continuities (e.g., in the correlates of EF) and contrasts (e.g., in the nature of EF and its neural substrates) and calls for research that compares developmental trajectories for EF in different groups (e.g., children with autism vs. ADHD). In addition, findings highlight the importance of environmental influences on EF and so support the development of interventions to promote EF and hence improve children’s academic and social outcomes.</p>

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Changes and challenges in 20 years of research into the development of executive functions

Claire Hughes

Centre for Family Research,

University of Cambridge,

Free School Lane, Cambridge CB2 3RF, UK

For Peer Review

Abstract

This review of 20 years of developmental research on Executive Functions (EF) offers a broad-brushstroke picture that touches on multiple issues including: (i) findings from typical and atypical groups, from infancy to adolescence; (ii) advances in assessment tools and in statistical analysis; (iii) the interplay between EF and other cognitive systems (e.g., those involved in children's developing understanding of mind, and in their processing of reward signals); (iv) integration of cognitive and neuroscience perspectives on EF; and (v) environmental factors that have either a positive influence (e.g., training/intervention programmes; parental scaffolding) or a negative influence (e.g., maltreatment, neglect, traumatic brain injury) on EF. Of the several themes to emerge from this review, two are particularly important; these concern the need to adopt developmental perspectives and the potential importance for intervention work of research on social influences on EF. Specifically, the review highlights both developmental continuities (e.g., in the correlates of EF) and contrasts (e.g., in the nature of EF and its neural substrates) and calls for research that compares developmental trajectories for EF in different groups (e.g., children with autism vs. ADHD). In addition, findings from both family-based research and randomized controlled trials of school-based interventions highlight the importance of environmental influences on EF and so support the development of interventions to promote EF and hence improve children's academic and social outcomes.

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Executive Function (EF) is an umbrella term that encompasses the higher-order processes (such as inhibitory control, working memory, attentional flexibility) that govern goal-directed action and adaptive responses to novel or complex situations. For much of the last century, research on EF focused on adults rather than children; as noted elsewhere (Hughes & Graham, 2002), this prolonged neglect of developmental perspectives on EF can be explained in at least three ways. First, the pre-frontal cortex, widely considered as the neural substrate for EF, was thought to mature very late, around adolescence (Golden, 1981). Second, primate studies and early research on head-injuries suggested that the consequences of juvenile lesions to the prefrontal cortex did not become apparent until adulthood (the so-called ‘Kennard effect’). Third, because they were designed for adults, early EF tests were typically too difficult to be appropriate for use with children.

Over the past few decades, developmental EF research has grown exponentially: a recent Scopus search using the terms ‘EF’ and ‘children’ showed 26 hits between 1980 and 1990, 216 hits between 1990 and 2000, and 1,092 hits between 2000 and 2010. What insights have emerged from this remarkable increase in research interest in EF in childhood? To celebrate *Infant and Child Development*’s 20th birthday, this review addresses this question by considering developmental EF research over the journal’s lifetime in relation to five themes. The first two of these concern the nature and significance of EF deficits in clinical groups and links between individual differences in EF and in children’s understanding of mind. These two themes were central to an EF special issue of *Infant and Child Development* that appeared in 2005 (for an overview, see Hughes, 2002) and so are discussed only briefly in the current paper. The next two themes are the need to attend to methodological issues in both task design and in analysis and, building on this, the

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2
3 importance of adopting developmental perspectives to construct more dynamic models of
4 individual differences in EF. Although methodological issues were discussed in the 2005
5 ICD special issue, recent years have seen striking progress in the analysis of data from
6 developmental EF studies and so these themes are discussed in more detail in this paper.
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8 The final theme represents a shift from science to practice and consider social influences on
9 EF development, including both positive and negative effects of family environments and
10 the efficacy of school-based interventions.
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20 *(1) EF deficits in clinical groups*
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22 Over the past 20 years, EF deficits have been reported for numerous clinical groups,
23 ranging in age from infancy through to adolescence. For example, in a landmark study,
24 Diamond, Prevor, Callender and Druin (1997) examined very young children treated early
25 and continuously for phenylketonuria (PKU), a metabolic disorder that affects infants'
26 ability to convert phenylalanine to tyrosine (the precursor of dopamine) and that, if
27 untreated, is the most common biochemical cause of developmental delay. Highlighting
28 the importance of dopamine for EF, Diamond et al. (1997) found that, across all ages (6
29 months to 7 years) within the PKU group, high plasma levels of phenylalanine predicted
30 poor performance on tests of working memory and inhibitory control.
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43 More recent studies have revealed that premature birth and prenatal exposure to
44 high levels of alcohol are also associated with long-term EF deficits. In a recent meta-
45 analysis of EF in children born prematurely, Mulder, Pitchford, Hagger and Marlow (2009)
46 found that severity of EF impairment was related to: (i) gestational age (extremely
47 premature infants showed greater EF deficits); (ii) age at test (group differences attenuated
48 with age); and (iii) aspect of EF under test ('catch-up' effects were evident for selective
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3 attention skills but not for attention set-shifting skills). EF deficits in children with prenatal
4 alcohol exposure have yet to be systematically reviewed, but are widely reported to be
5 independent of IQ (e.g., Connor, Sampson, Bookstein, Barr, & Streissguth, 2000; Green et
6 al., 2009; Mattson, Goodman, Caine, Delis, & Riley, 1999; Schonfeld, Mattson, Lang,
7 Delis, & Riley, 2001) and distinct from EF deficits in other groups, such as children with
8 attention deficit hyperactivity disorder (ADHD) (e.g., Vaurio, Riley, & Mattson, 2008).
9 Together, these findings highlight both the sensitivity of EF to neurological challenges and
10 the fractionated nature of EF.
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22 Moving on to preschool milestones, much of the clinical literature has concerned
23 EF deficits in children with autism (for reviews, see Hill, 2004; Pennington & Ozonoff,
24 1996). The breadth and sophistication of current research in this field are nicely illustrated
25 by a handful of recent findings that include: (i) evidence for associations between impaired
26 inhibitory control and high-level repetitive behaviors (e.g., compulsions, preoccupations) in
27 children with autism spectrum disorders (Mosconi et al., 2009); (ii) experimental evidence
28 that suggests that the deficits in pretend play shown by children with autism reflect
29 impairments in generativity rather than in meta-representation of mental states (Jarrold,
30 Mansergh, & Whiting, 2010); (iii) imaging results that indicate reduced functional
31 connectivity and network integration between frontal, parietal, and occipital regions among
32 individuals with autism spectrum disorders completing EF tasks (Solomon et al., 2009);
33 (iv) longitudinal evidence for the importance of early EF in shaping the developmental
34 trajectory of theory-of-mind skills in children with autism spectrum disorders (Pellicano,
35 2010); and (v) evidence for age-related improvements in executive function from childhood
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3 to adolescence in autism, indicating the presence of plasticity and suggesting a prolonged
4 window for effective treatment (for a review, see O'Hearn, Asato, Ordaz, & Luna, 2008).
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8 Among school-aged children, clinical EF studies typically focus on children with
9 ADHD who, by definition, show marked problems of impulsivity / inattention /
10 disorganization in their everyday lives. Interestingly, comparisons of clinical groups show
11 that EF deficits are typically less pervasive and severe among children with ADHD than
12 among children with autism (e.g., Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004;
13 Goldberg et al., 2005; but see also Happé, Booth, Charlton & Hughes, 2006). As a result,
14 contemporary causal accounts of ADHD (e.g., Sonuga-Barke, 2005) also include additional
15 deficits in the signaling of delayed rewards.
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27 In adolescence, clinical studies again highlight a close interplay between EF and
28 reward systems. For example, poor EF and impulsivity in late childhood predict high levels
29 of drug use in late adolescence (e.g., Aytaclar, Tarter, Kirisci, & Sandy, 1999). Similarly,
30 Wiers et al. (2007) proposed that repeated alcohol use in adolescence leads to compromised
31 EF development coupled with sensitization of appetitive reward systems. In addition,
32 Fairchild et al. (2009) found that although boys with conduct disorder (especially early-
33 onset conduct problems) showed no EF deficits when effects of IQ were controlled, they
34 were more likely to make risky choices even for small gains, suggesting an atypical balance
35 between sensitivity to reward and punishment. In short then, clinical studies of EF in older
36 children and adolescents highlight the importance of examining the interplay between top-
37 down EF systems and bottom-up reward processes; this interplay is discussed later on in
38 this paper.
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55 2) *Associations between individual differences in EF and in understanding of mind.*
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3 Almost 20 years ago, researchers examining the factors underpinning autistic children's
4 poor false belief performance highlighted associations with emerging EF skills (e.g.,
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6 Hughes & Russell, 1993; Ozonoff, Pennington, & Rogers, 1991). Since then, research in
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8 this field has grown in at least three directions. The first of these is a dramatic growth in the
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10 variety of samples involved: there is now evidence for a robust association between EF and
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12 theory of mind in several different clinical groups, including children with autism (e.g.,
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14 Pellicano, 2007), children with hyperactivity or conduct problems (Hughes, Dunn, &
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16 White, 1998), children with traumatic brain injuries (Dennis, Agostino, Roncadin, & Levin,
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18 2009), and children with fetal alcohol syndrome (Rasmussen, Wyper, & Talwar, 2009). In
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20 addition, amongst typically developing samples, this link between EF and understanding of
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22 mind has been documented at several different periods of development, from toddlerhood
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24 (e.g., Carlson, Mandell, & Williams, 2004; Hughes & Ensor, 2005) to adolescence
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26 (Dumontheil, Apperly, & Blakemore, 2010).
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34 Expanding the developmental scope of research into associations between EF and
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36 theory of mind has led to more nuanced theoretical accounts, including, for example, the
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38 proposal that the relationship between EF and theory of mind is developmentally dynamic.
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40 In particular, in a critique of the original theory-of-mind account of autism (which is often
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42 diagnosed long before children are expected to pass false belief tasks), Tager-Flusberg
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44 (2001) proposed that early-onset 'socio-perceptual' skills (aka intuitive mentalising)
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46 depend on modular cognitive processes, whereas later-onset 'socio-cognitive' skills (aka
47
48 off-line mental-state reasoning) depend on other aspects of cognition, such as language and
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50 EF. This model of dual processes (e.g., Apperly, Samson, & Humphreys, 2009; de
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52 Vignemont, 2009) also goes some way to explaining why typically-developing young
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3 children can show quite sophisticated mentalising skills in their everyday interactions and
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5 yet fail experimental false-belief tasks.
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8 The second direction of growth in research on links between EF and theory of mind
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10 concerns the number of longitudinal studies; these have been conducted using a variety of
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12 age groups and also vary in temporal span, from short-term microgenetic studies (e.g.,
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14 Flynn, 2006) to studies involving intervals of up to 24 months (Carlson, Mandell, &
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16 Williams, 2004; Hughes & Ensor, 2007). One consistent finding to emerge from all of
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18 these longitudinal studies is that early EF predicts later mental-state awareness more
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20 strongly than early mental-state awareness predicts later EF. Without going as far as
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22 stipulating that EF is, in some sense, necessary for the emergence of mental-state
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24 awareness, it seems reasonable to argue that EF improvements in the preschool years help
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26 explain how children *make use* of their early intuitive understanding of mind. The third
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28 and final direction of progress is the growth of studies that link EF and theory of mind to
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30 common neural substrates (for reviews, see Perner & Aichhorn, 2008; Perner, Aichhorn,
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32 Kronbichler, Staffen, & Ladurner, 2006). This literature is discussed at the end of the next
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34 section.
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40 *3) Methodological issues in assessment and analysis*

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43 The past 20 years have seen impressive and wide-ranging methodological improvements in
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45 research on EF in childhood. This section provides a brief summary of five distinct areas
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47 of improvement: (i) the development of child-friendly tasks; (ii) the development of
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49 computerized tasks; (iii) greater attention to issues of ecological validity; (iv) an increase in
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51 the rigor and sophistication of statistical analyses; and (v) the combination of
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53 neuropsychological and neuro-physiological assessments.
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Child-friendly tasks. As noted at the start of this review, the delayed emergence of developmental perspectives on EF can at least in part be explained by the scarcity of developmentally appropriate measures. Indeed, a dramatic increase in the availability of child-friendly tasks is perhaps the most striking change over the past two decades of developmental EF research. Moreover, studies of children's performances on these simpler tasks have, in many ways, minimized many of the problems associated with measuring EF in adults (Hughes & Graham, 2002).

That said, as Garon, Bryson and Smith (2008) noted in their recent review (which includes a helpful summary of EF tasks for very young children), in simplifying EF tasks for children there is a real danger of losing the critical EF component. In addition, many EF tasks have relatively weak psychometric properties (e.g., Bishop, Aamodt-Leeper, Creswell, McGurk, & Skuse, 2001). For each of these reasons, it is possible that age-contrasts in children's performances on EF tasks actually reflect non-EF influences on performance. This point has particular force for specific developmental periods (e.g., children's transition to school) that are characterized by improvements in salient non-EF factors (e.g., language ability, pragmatic understanding, and compliance). To address this concern, Hughes, Ensor, Wilson and Graham (2010) tracked children's EF scores from ages 4 to 6 (i.e., from preschool to school age). Their analyses showed that latent EF factors showed a reassuringly good fit to the data, even when potential effects of measurement artifacts were removed by holding the metric constant across time points.

Computerized tasks. From a research perspective, computerized tests of EF have a number of benefits; these include the ease of standardizing administration and collecting data from a large numbers of trials, including information about reaction times. One widely

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2
3 used battery of computerized EF tasks is the CANTAB (CAmbridge Neuropsychological
4 Tests - Automated Battery), which was developed for work with adult clinical groups
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6 (Luciana, 2003) and was first administered to children in Hughes, Russell and Robbins'
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8 (1994) study of children with autism; subsequent studies have confirmed that the CANTAB
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10 is sensitive to EF deficits in autism across a wide range of ages and ability levels (Ozonoff
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12 et al., 2004). Normative data on age-related improvements in EF in typically developing
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14 children (screened to exclude children with learning or behavioral difficulties) have also
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16 been gathered (Luciana, 2003). However, computerized tasks appear less sensitive than
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18 manual tasks to EF deficits in clinical groups, such as children with autism (Ozonoff,
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20 1995), and have also been criticized as having poor ecological validity, a topic that is
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22 considered in more detail below.
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29 *Ecological validity.* Individuals with frontal damage often show intact performance
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31 on EF tasks, yet appear impulsive and disorganized in their everyday lives (Levine et al.,
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33 2000). Over the past 20 years, this issue of ecological validity has been addressed in two
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35 distinct ways. First, in a new generation of EF tasks, open-ended problems are used to
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37 index the 'multi-tasking' skills required by many practical situations (e.g., shopping or
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39 cooking). The first of these new tasks were designed for adults, but over the past decade a
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41 number of open-ended tasks have also been designed for children. For example, the
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43 children's version of the Behavioural Assessment of Dysexecutive Syndrome (BADS-C;
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45 Emslie, Wilson, Burden, Nimmo-Smith & Wilson (2003) includes tests of practical
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47 problem solving (e.g., planning a trip around a zoo; conducting a systematic search of an
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49 area for a missing small object; using water to get a cork out of a container) and now has
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51 norms available for children aged 7 to 16 years. Interestingly, a recent study of autism that
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3 involved a battery of EF tasks showed that the open-ended tasks on the BADS-C were
4 particularly sensitive to group differences between children with autism and their age- and
5 IQ-matched controls (White, Burgess, & Hill, 2009). Recently, another study involving
6 older children and teenagers used a practical EF task in which participants display their
7 multi-tasking skills by following recipe instructions for two simple dishes in tandem;
8 scores on this cooking task show good test-retest reliability, converge with scores on other
9 EF measures, and appear sensitive to the EF deficits shown by children with traumatic
10 brain injury (Chevignard, Catroppa, Galvin, & Anderson, 2010).
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24 Second, researchers have begun to broaden the nature of EF assessments by
25 including parent questionnaires designed to index children's everyday EF skills. For
26 example, alongside the practical tasks described above, the BADS-C includes a parent
27 questionnaire (DEX-C) that is now widely used for assessing children with a wide
28 spectrum of developmental and acquired neurological conditions. Another such
29 questionnaire is the 'Behavioral Rating Inventory of Executive Function' (BRIEF- Gioia,
30 Isquith, Retzlaff, & Espy, 2002), which includes a parallel teacher version that enables EF
31 skills to be assessed in both home and school environments. The BRIEF provides 8 distinct
32 scales, of which three (Inhibit, Shift, Emotional Control) index Behavioural Regulation and
33 five (Initiate, Working Memory, Plan/Organize, Organization of Materials, Monitor) index
34 Metacognition. These 8 scales are based on 86 items, such that the acronym BRIEF is
35 perhaps somewhat misleading. However, a recent study has demonstrated that an
36 abbreviated version of the parental questionnaire shows good psychometric properties
37 (Lejeune et al., 2010). That said, another recent study (McAuley, Chen, Goos, Schachar, &
38 Crosbie, 2010) concluded that scores on the BRIEF provide a good index of everyday
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3 problems, but show relatively weak associations with scores on direct tests of EF. In
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5 contrast, Carlson and Wang (2007) reported that, for typically developing preschoolers at
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7 least, experimental measures of EF show strong associations with scores on a much older
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9 rating scale, designed to index normative individual differences and age-related changes in
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11 children's 'self control' (Kendall & Wilcox, 1979). However, no study has examined EF
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13 task performances in relation to scores on both the BRIEF and the Self Control rating
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15 scales; this comparison is needed to rule out the possibility that these contrasting results
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17 reflect differences in the samples or in the ecological validity of the tasks used, rather than
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19 real differences in the constructs tapped by these two questionnaire measures.
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26 *Statistical Analyses.* Studies of EF in childhood have also advanced through the
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28 use of more rigorous methods of statistical analysis, including confirmatory factor analysis
29
30 (CFA), item response theory (IRT) and latent growth models (LGMs). For example, in a
31
32 seminal study Miyake and colleagues (Miyake et al., 2000) used confirmatory factor
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34 analysis (CFA) to demonstrate 'unity and diversity' in the structure of EF in adults.
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36 Interestingly, subsequent studies that applied CFA to data from children suggest that EF in
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38 preschoolers has a simple unitary structure (e.g., Hughes, Ensor, Wilson, & Graham, 2010;
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40 Wiebe, Espy, & Charak, 2008; Wiebe et al., 2010), but shows a more fractionated structure
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42 in school-aged children (Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi,
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44 Kooistra, & Pulkkinen, 2003). That is, as noted by Wiebe et al. (2010), dramatic
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46 improvements in the efficiency of EF in the preschool years appear to be accompanied by
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48 fundamental changes in the structure of EF.
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54 Very recently, Willoughby, Wirth and Blair (2010) have applied IRT to assess the
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56 psychometric properties of a battery of EF tasks for preschoolers. IRT is an example of
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3 modern measurement theory, and addresses several problematic assumptions inherent
4 within classical test theory (CTT). In particular, CTT assumes that: (i) individual items on
5 a given task are interchangeable (such that actual scores reflect true ability); and (ii)
6 measurement precision for a task does not vary for children of different ability levels (such
7 that task scores work equally well for distinct subgroups of children). In contrast, IRT
8 allows one to plot 'item characteristic curves' (ICCs) that provide information about both
9 the difficulty and discrimination of specific items within a task; the information in these
10 ICCs can then be aggregated to provide 'total information curves' that summarize how well
11 a particular task discriminates between performance across children of varying abilities. In
12 addition, IRT allows one to test for differential item functioning by comparing item
13 parameters (e.g., difficulty, discrimination) across different groups (e.g., boys / girls;
14 preschoolers / school-aged children; participants from low / high income families).
15 Applying this approach, Willoughby et al. (2010) were able to show that three distinct EF
16 tasks (a self-ordered search test of working memory, a 'Silly Sounds' non-verbal Stroop
17 test of inhibitory control, and an attention set shifting task) showed similar ICCs over
18 repeated intervals and for children from low-income vs. high income families, but differed
19 markedly with regard to task information. Specifically, the inhibitory control task provided
20 very good reliability over a narrow range of ability, but the working memory and
21 attentional set shifting task provided moderate reliability over a broad range of ability
22 levels. These contrasts in psychometric properties highlight the challenges facing
23 researchers investigating developmental change in the nature of EF and indicate that
24 conclusions about structural change (e.g., a shift from a unitary to a fractionated construct)
25 can only be made with considerable caution.
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3 To add to the complexity, studies of age-related improvements in EF performance
4 often overlook variation in growth, but recent work using latent growth models (LGMs)
5 highlight the importance of attending to individual differences in the rate at which children
6 improve their EF skills. Specifically, in a study that tracked EF skills for 191 children who
7 were followed from age 4 to age 6 (i.e., across the transition to school), Hughes and Ensor
8 (2010) found that, even when effects of concurrent individual differences in verbal ability
9 and EF were controlled, variation in EF slopes predicted individual differences in both
10 teacher-rated problem behaviours and self-rated academic competence. That is, when
11 assessing the relationship between children's cognitive performance and their behavior /
12 self-concepts, children's growth (rather than their actual performance) appears to be what
13 really matters.
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29 *Integration with neurophysiological assessments.* Over the past two decades, a
30 key advance within research on EF development has been the increased integration
31 between cognitive and neuroscience perspectives. For example, recent studies using
32 functional magnetic resonance imaging (fMRI – for a review, see Tau & Peterson, 2010)
33 have been able to confirm the view that developmental improvements in EF coincide with
34 age-related increases in the activation of dopamine rich frontal and striatal circuits. This
35 integration of cognitive and biological assessments has, in turn, led to greater recognition
36 of the interplay between social and biological influences on children's development. This
37 is well illustrated by recent findings that provide a fresh perspective on the mechanisms
38 underpinning associations between EF and theory of mind (discussed earlier).
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52 Specifically, alongside evidence that dopaminergic systems are involved in
53 children's EF development, findings from recent studies using electro-encephalogram
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(EEG) recordings suggest that dopamine pathways are also implicated in children's growing understanding of mind (Sabbagh, Bowman, Evraire, & Ito, 2009). Moreover, dopamine systems may contribute to social influences upon children's growing understanding of mind (Lackner, Bowman, & Sabbagh, 2010). Specifically, by regulating the activity of fronto-striatal circuits in order to respond flexibly to environmental feedback (e.g., Montague, Hyman, & Cohen, 2004), dopamine is likely to contribute to children's ability to reflect on (and revise) their own concepts of mind in order to accommodate new information from the environment. Variation in this ability to shift expectations and goals (e.g., as indexed by strategic decision-making in gambling tasks) may, in turn, be pivotal to accounts of how family environment factors (such as frequencies of family conversations about mental states, or interactions with siblings) lead to individual differences in children's theory-of-mind development (Perner, Ruffman, & Leekam, 1994). In other words, alongside possible mediation effects of social interactions on the relation between EF and theory of mind, EF (and closely related reward functions of the dopaminergic systems) may moderate the impact of social interactions on children's developing understanding of mind. To my knowledge, this proposal has yet to be tested.

4) Developmental perspectives

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. EF skills begin to emerge in infancy (Diamond, 1988), show marked improvements across toddlerhood and the preschool period (Carlson, Mandell, & Williams, 2004; Hughes & Ensor, 2007; Hughes, Ensor, Wilson, & Graham, 2010) and continue to improve across the school years (e.g., Huizinga, Dolan, & van der Molen, 2006), with some

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3 aspects of EF continuing to develop throughout adolescence (Luciana, Conklin, Cooper, &
4 Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004). Interestingly, although
5 several reviews of EF development are available (e.g., P. Anderson, 2002; Best, Miller, &
6 Jones, 2009; Blair, Zelazo, & Greenberg, 2005; Blakemore & Choudhury, 2006; Garon,
7 Bryson, & Smith, 2008; Hughes & Graham, 2002) very few span the full period of
8 development (for an exception, see Diamond, 2002). To rectify this gap, this section
9 provides a brief outline of key findings from developmental studies of EF, from infancy to
10 adolescence.
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22 *Infancy.* Evidence that EF emerges in the first year of life first came from studies
23 using Piaget's object permanence task, in which babies are repeatedly allowed to retrieve
24 an attractive object from one location (A) before seeing it hidden at a new location (B).
25 Early studies indicated that while babies aged 8 months or older typically search correctly
26 at location B, 5-month-olds persist in searching for the object at location A (e.g., Harris,
27 1975). However, later studies that used looking times rather than physical reaches to assess
28 perceptual understanding, showed that even 5-month-olds could succeed on this task (e.g.,
29 Baillargeon, Spelke, & Wasserman, 1985; Cuevas & Bell, 2010). Thus young babies who
30 make the 'A not B' error in their reaching responses may know that the object has been
31 moved, but fail to inhibit their previously successful (and thus prepotent) reach to A.
32 Success on this task can therefore be seen as reflecting infants' growing cognitive
33 flexibility and volitional control (Diamond & Goldman-Rakic, 1989). Other tasks that also
34 demonstrate early executive skills in infancy include a detour-reaching task, in which
35 infants are invited to retrieve an object that is visible behind a Perspex screen; success on
36 this task depends on making a 'detour reach' around the side of the screen (Diamond, Zola-
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3 Morgan, & Squire, 1989). On this task, a rudimentary ability to inhibit prepotent responses
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5 is clearly evident by 7–12 months (Diamond, 2002).
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8 More recent infant studies also indicate an early emergence of other aspects of EF,
9
10 such as executive attention. For example, building on Rothbart, Ellis, Rueda and Posner's
11
12 (2003) finding that anticipatory looking (i.e., looking to the location of a target prior to its
13
14 appearance) in 2-year-olds is associated with parental ratings of self-regulation, Sheese and
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16 colleagues (Sheese, Rothbart, Posner, White, & Fraundorf, 2008) reported that 6- and 7-
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18 month-olds who display high levels of anticipatory looking also show more signs of self-
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20 regulation in their approach towards novel toys. Interestingly, in this study anticipatory
21
22 regulation in their approach towards novel toys. Interestingly, in this study anticipatory
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24 looking was also associated with looking away from disturbing stimuli (face masks),
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26 supporting proposed links between early systems of emotional and cognitive control (e.g.,
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28 Aksan & Kochanska, 2004; Rothbart, Derryberry, & Hershey, 2000).
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32 *Preschoolers.* Research into the preschool years accounts for the lion's share of
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34 recent studies of EF in childhood. This focus on preschoolers reflects both the intensity of
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36 research into preschoolers' understanding of mind and the recent availability of age-
37
38 appropriate tasks. However, even when these conceptual and methodological factors are
39
40 taken into account, the growth of research on preschool EF remains remarkable and is
41
42 difficult to summarize briefly. Fortunately, Garon et al.'s (2008) recent comprehensive
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44 review is helpful in at least two respects. First, addressing the question of how to
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46 characterize developmental changes in EF across the preschool years, Garon et al. (2008)
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48 highlight the importance of age-related improvements in attention and coordination of
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50 distinct EF components. As they observe, attention also appears central to theoretical
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52 accounts that characterize EF development in terms of increased ability to integrate
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3 conflicting rules (Zelazo, Muller, Frye, & Marcovitch, 2003) or to overcome prepotent
4 thoughts / acts (Diamond, 2002) or latent representations (Munakata, 2001).
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8 Second, Garon et al. (2008) offer a number of suggestions for future research.
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10 One suggestion (discussed more fully in the next section of this paper) concerns the
11 importance of studying environmental influences on EF. Another suggestion concerns the
12 need for studies of developmental changes in EF to adopt a longitudinal design in order to
13 control for individual differences in EF. In one such study, Hughes et al. (2010) found: (i)
14 measurement invariance across latent factors for EF in preschool and early school age
15 (supporting the validity of across-time comparisons of average EF performance); (ii)
16 positive associations between variation in preschool EF and differences in both maternal
17 education and early child verbal ability; and (iii) inverse relations between rates of growth
18 in EF and verbal ability (such that preschoolers with low verbal ability begin to catch up
19 with their peers following the transition to school) but not maternal education (i.e., children
20 with less educated mothers show no independent catch-up effect). As these findings
21 illustrate, adopting longitudinal study designs to examine developmental trajectories in
22 early EF is valuable, both theoretically and for the development of educational policy.
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41 *School age.* A key finding to emerge from studies of EF across the school years is
42 that step-wise improvements are evident at different ages for different aspects of EF. For
43 example, while (as noted earlier) the preschool years are characterized by dramatic
44 improvements in inhibitory control, studies of young school-aged children highlight
45 improvements in cognitive flexibility. For example, Luciana (2003) reported that around
46 the age of 6 or 7 years children showed a marked improvement in their ability to shift
47 mental set (e.g., to attend to a previously irrelevant dimension when choosing which of two
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3 stimulus patterns is 'correct' – in a multi-stage task based on the Wisconsin Card Sorting
4 Task), whereas clear improvements on the Tower of London planning task or on a self-
5 ordered search test of working memory in the CANTAB were often not evident before the
6 age of 11 or 12 years. Other studies using different tasks have reported a similar contrast in
7 the developmental trajectories of different aspects of EF. For example, several studies
8 report improvements in mental flexibility around age 8 years (e.g., P. Anderson, 2002; W.
9 W. Anderson, Damasio, Tranel, & Damasio, 2001) while planning, organizing and strategic
10 thinking are typically reported to emerge later and to show age-related improvements
11 throughout adolescence (P. Anderson, Anderson, & Garth, 2001; P. Anderson, Anderson,
12 & Lajoie, 1996; De Luca et al., 2003; Krikorian, Bartok, & Gay, 1994; Welsh, Pennington,
13 & Groisser, 1991).

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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, Amso, Anderson, & Diamond, 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 at a gross level, but require effort, to work in a more selective manner, such that 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 tasks (such as that used in Davidson et al.'s (2006) study) involving 'mixed block' designs that require them to switch repeatedly between dominant and sub-dominant responses,. 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

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3 made errors on difficult trials. These contrasting speed accuracy trade-offs highlight the
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5 value of using computerized tasks to assess EF.
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8 *Adolescence.* Recent technological advances have also led to significant progress in
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10 documenting parallels between milestones in EF development in adolescence and changes
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12 in brain myelination. This progress is particularly evident in Giedd et al.'s (1999) large-
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14 scale longitudinal MRI work on adolescence, which has shown that this period is
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16 characterized by both a linear increase in white matter and a non-linear decrease in grey
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18 matter. Gains in white matter have clear functional consequences, which include faster and
19
20 more efficient sharing of information within the fronto-striatal circuits and smoother
21
22 communication between the frontal cortex and other brain regions (Paus, 2010). Peak
23
24 periods of reduction in grey matter occur just after puberty and at the transition from
25
26 adolescence to adulthood; although typically attributed to synaptic pruning, this 'loss' of
27
28 grey matter may simply reflect gains in white matter (Paus, 2010). As noted in a recent
29
30 review (Blakemore & Choudhury, 2006), structural changes in the adolescent brain are
31
32 particularly evident in the frontal cortex and are linked to age-related improvements in
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34 inhibitory control (Luna, Garver, Urban, Lazar, & Sweeney, 2004), working memory (e.g.,
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36 Luciana, Conklin, Cooper, & Yarger, 2005) and decision-making (e.g., Hooper, Luciana,
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38 Conklin, & Yarger, 2004).
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46 Consistent with the findings from younger samples described above, different
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48 aspects of EF have been reported to show distinct trajectories across the adolescent years.
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50 For example, in a study of Australian 11- to 17-year-olds that included a variety of EF
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52 tasks, Anderson, Anderson, Northam, Jacobs and Catroppa (2001) found clear linear age-
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3 related improvements on tests of selective attention, working memory and problem solving,
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5 but no age-related difference in planning performance.
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8 Also echoing findings from studies of younger samples is an emerging theme from
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10 the adolescent literature regarding the need to consider individual differences in both the
11
12 maturity of adolescents' EF functions and the extent to which they avoid risk and respond
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14 to reward / peer influence (adolescents are less risk-averse, more driven by reward, and
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16 more easily influenced by peers). Thus accounts of developmental change in everyday
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18 behavior should consider the interplay between top-down EF systems and bottom-up
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20 motivational and emotional responses to situations of risk and reward.
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25 Similar conclusions emerge from a recent community-based study of relations
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27 between EF, problem behaviors and risk-taking in 10-12-year-olds (Romer et al., 2009). In
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29 this study, the children's self-reported impulsivity was inversely related to both working
30
31 memory and reversal learning and explained individual differences in both externalizing
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33 problems and performance on a risk-taking task. Noting that interventions to improve
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35 children's working memory have led to reductions in impulsive behaviors (e.g., Klingberg
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37 et al., 2005), the authors of this study concluded that young people who have difficulties in
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39 considering multiple (and potentially conflicting) goals will be less likely either to 'look
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41 before they leap' or to temper their interest in novel or exciting experiences.
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45 46 *5) Social influences on EF development*

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48 The frontal cortex and its networks mature very gradually and so are heavily dependent on
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50 the environment (e.g., Noble, Norman, & Farah, 2005). Yet, compared with the large body
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52 of biological studies of EF development (for a recent review of molecular genetic studies of
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54 EF in children, see Brocki, Clerkin, Guise, Fan, & Fossella, 2009), very few studies have
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2
3 examined the processes underpinning environmental influences on EF. This lack of
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5 empirical research is surprising, given that an emphasis on the importance of social
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7 influences on EF is prominent in both early theoretical work (e.g., Luria, 1966; Vygotsky,
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9 1978) and more recent accounts (Lewis & Carpendale, 2009). That said, work in this field
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11 is now growing rapidly and currently encompasses at least three key issues: (i) positive
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13 influences of parent-child interactions on EF; (ii) effects of adverse family environments;
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15 and (iii) effects of training or intervention programs. These are described in more detail
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17 below.
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22 *Positive effects of parent child interactions.* Carlson (2003) has proposed that three
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24 dimensions of adult-child interactions are likely to favour child EF. The first two of these –
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26 *scaffolding* (which provides children with successful experiences of problem-based
27
28 learning) and *mind-mindedness* (which provides children with verbal tools for progressing
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30 from external to internal forms of self-regulation) – each feature prominently in two
31
32 randomized controlled trials (discussed below). Positive effects on EF of the third
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34 dimension of *sensitivity* (which provides infants with successful experiences of impacting
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36 on the environment) have been reported by Bernier, Carlson and Whipple (2010), in their
37
38 recent longitudinal study of 80 infants, in which all three dimensions of parenting
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40 (evaluated at 12 to 15 months of age) predicted EF at 18 and 26 months. Once effects of
41
42 maternal education and general cognitive ability were taken into account, however,
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44 scaffolding was the strongest predictor of EF at each age. Another recent study, conducted
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46 by Bibok, Carpendale and Muller (2009), offers a refinement of how parental scaffolding
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48 may promote young children's EF skills (indexed by performance on an attention-
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50 switching task). Specifically, observations of parents scaffolding children's goal-directed
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3 activities revealed that the *timing* of parents' elaborative utterances was a key predictor of
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5 children's attention-switching skills.
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8 In short, there is now good evidence that parents' deliberate efforts to scaffold
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10 children's goal-directed activities do indeed foster the development of early EF skills. But,
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12 as highlighted by research on children's developing social understanding, family influences
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14 are often incidental rather than deliberate. Support for this view comes from a recent
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16 longitudinal observational study by Hughes and Ensor (2009) involving a socially diverse
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18 sample of 125 children. In this study both maternal scaffolding (in structured play with
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20 jigsaws) and opportunities for observational learning (indexed by maternal strategic
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22 behavior in a multi-tasking paradigm and in a shared tidy-up task) predicted improvements
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24 between the ages of 2 and 4 in children's EF scores, even when effects of verbal ability
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26 were controlled. Note that including EF assessments at both time-points enabled Hughes
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28 and Ensor (2009) to take the temporal stability of individual differences in EF into account,
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30 and so minimize the confounding effects of genetic factors (Kovas, Haworth, Dale, &
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32 Plomin, 2007).
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38 *Negative effects of adverse family environments.* Alongside the positive
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40 associations between EF and both deliberate and incidental opportunities to learn from
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42 parents' playful behaviour, Hughes and Ensor (2009) also found that EF development from
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44 age 2 to age 4 was *negatively* correlated with parental ratings of disorganised and
45
46 unpredictable family life, suggesting that families can hinder as well as help young
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48 children's emerging EF skills. Indeed, clinical studies indicate that unfavourable early
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50 environmental experiences adversely affect both brain structure (e.g., De Bellis, 2005) and
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52 function (e.g., Rutter & O'Connor, 2004). These adverse effects may be especially clear for
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3 children's developing EF skills. For example, a recent study of internationally adopted
4 children (exposed to severe adverse early environments) demonstrated good catch-up in
5 many specific areas of development, but persistent difficulties in EF and attentional
6 regulation (Jacobs, Miller, & Tirella, 2010). Other clinical studies of children who have
7 experienced maltreatment or severe neglect highlight the impact of such extreme adverse
8 environments on neuroendocrine and autonomic stress reactivity, which in turn leads to
9 increased demands on EF systems of regulatory control (e.g., Bierman, Nix, Greenberg,
10 Blair, & Domitrovich, 2008; Cicchetti, 2002). Note also that environmental influences
11 often show substantial interactions with genetic factors, such that genetic vulnerability is
12 only expressed among individuals exposed to environmental stressors, such as harsh
13 parenting or family chaos (Asbury, Dunn, Pike, & Plomin, 2003; Asbury, Wachs, &
14 Plomin, 2005).

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16 Findings from children with traumatic brain injury indicate that higher-order brain
17 functions (such as EF) are particularly vulnerable while they are still emerging. In their
18 recent review of the effects of early brain injury on EF, Anderson et al. (2010) examined
19 findings from children with focal brain pathology evident on MRI scan and compared EF
20 performance in late childhood or adolescence for children who sustained early brain injury
21 at each of six developmental periods (Congenital / Peri-natal / Infancy / Preschool / Mid
22 Childhood / Late Childhood), with these six groups being matched for gender, SES, lesion
23 size, location or laterality. Their findings showed that children who experienced brain
24 injury very early in life displayed markedly more severe deficits in EF (and IQ). In other
25 words, while the development of EF can be disrupted, with either transient or more
26 permanent consequences, once established, EF skills are relatively robust (Johnson, 2005;
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3 Thomas & Johnson, 2008). Consistent with this view, while Hughes, Roman and Ensor
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5 (2011) have reported significant inverse relations between exposure to maternal depression
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7 and preschool EF, no such association has been found in studies of older children or
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9 adolescents with depressed mothers (Klimes-Dougan, Ronsaville, Wiggs, & Martinez,
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11 2006; Micco et al., 2009).
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15 *Training studies and interventions.* Intervention studies can be considered in two
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17 sets, of which the first set involves direct training on task analogues. For example, Kloo
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19 and Perner (2003) gave typically developing preschoolers a simplified version of the
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21 Wisconsin Card Sort task and found positive effects at post-test for both card-sorting
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23 training and false-belief training (each delivered in two sessions on separate days). More
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25 recently, Rueda et al. (2005) gave groups of 4- and 6-year-olds 5 days of attention training,
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27 and reported that low performers at pre-test showed the greatest gains, equivalent to half
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29 the difference between older and younger participants (i.e., the extent of gain expected
30
31 from one year's difference in age). Similarly, in a recent review, Klingberg (2010) reported
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33 that training leads to significant improvements in working memory across a wide variety of
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35 age groups. However, not all aspects of EF appear so malleable to training. For example,
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37 (Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009) found that a 5-week preschool
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39 training programme produced significant improvements in working memory but not in
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41 inhibitory control, suggesting that distinct processes underpin different aspects of EF.
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43 Finally, Karbach and Kray (2009) showed that training on task-switching led to positive
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45 effects that transferred to other EF tasks and to tests of fluid intelligence, both among
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47 school-aged children (aged 8- to 10-years) and in two groups of adults (aged 18- to 26-
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49 years and 62- to 76-years). Interestingly, varying the training tasks reduced the
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3 improvements in children but increased improvements in adults. Clearly then, intervention
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5 designs need to be developmentally sensitive.
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8 The second set of intervention studies adopt a broader and more naturalistic
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10 approach and are thus perhaps of greater relevance for theories of how everyday social
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12 environments might impinge on children's EF development. Randomized control trials
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14 (RCTs) have been used to assess at least three such interventions. The first of these, Head
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16 Start REDI (REsearch based, Developmentally Informed) is integrated into the Head Start
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18 pre-kindergarten programme for disadvantaged children and involves brief lessons, "hands-
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20 on" extension activities, and specific teaching strategies to promote social-emotional,
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22 "hands-on" extension activities, and specific teaching strategies to promote social-emotional,
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24 linguistic and literacy skills. Bierman, Nix, Greenberg, Blair and Domitrovich (2008)
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26 reported that the REDI intervention led to significant improvements in children's task
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28 orientation, coupled with marginally significant gains in set-shifting performance. Another
29
30 well-recognized intervention is the Vygotskian 'Tools in the Mind' preschool curriculum
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32 (Bodrova & Leong, 1996; Diamond, Barnett, Thomas, & Munro, 2007), which includes a
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34 variety of specially designed activities (e.g., socio-dramatic play, shared reading) that
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36 enable children to progress from external- to shared- to self- regulation; teachers are also
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38 trained to foster early skills in literacy and mathematics by encouraging reflective thinking
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40 and metacognition. Interestingly, although language plays a pivotal role in Vygotskian
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42 accounts of cognitive development, the Tools curriculum did not have a significant impact
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44 on language development (Barnett et al., 2008) but did appear to improve children's EF
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46 skills (note however that EF was only indexed indirectly by low problem behavior scores).
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48 The third RCT focused on an 8-week school-based intervention for older children (7- to 9-
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50 year-olds) that aimed to promote mindful awareness practices (MAPs) through twice-
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3 weekly half-hour sessions. Echoing earlier results from preschoolers (e.g., Rueda, Rothbart,
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5 McCandliss, Saccomanno, & Posner, 2005), Flook, Smalley, Kitil, Galla, Kaiser-
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8 Greenland, Locke, Ishijima and Kasari (2010) reported that treatment-related gains in
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10 teacher and parent ratings of EF skills (both at school and at home) were particularly clear
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12 for less well-regulated children.
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17 *Conclusions*

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20 This review of two decades of developmental research on EF has covered considerable
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22 ground, including: (i) findings from typical and atypical groups across a broad
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24 developmental span (from infancy to adolescence); (ii) advances in assessment tools (e.g.,
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26 development of child-friendly tasks, construction of questionnaire measures) and in
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28 statistical analysis (e.g., modeling both the structure of EF and developmental trajectories
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30 for EF); (iii) the interplay between EF and other cognitive systems (e.g., those involved in
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32 children's developing understanding of mind, and in their processing of reward signals);
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34 (iv) integration of cognitive and neuroscience perspectives on EF (resulting in new models
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36 of how EF interacts with other cognitive systems); and (v) environmental factors that have
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38 either a positive influence (e.g., training/intervention programmes; parental scaffolding) or
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40 a negative influence (e.g., maltreatment, neglect, traumatic brain injury) on EF
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42 development.
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49 Given the breadth of this review, it is interesting that several overarching themes
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51 emerged across the different sections. These include both continuities and contrasts in the
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53 substrates and correlates of EF in children of different ages. For example, from infancy
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55 through to adolescence, poor EF appears to be associated with risk taking and sensation
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3 seeking; this association highlights a developmental continuity in the interplay between
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5 top-down systems of EF and bottom-up reward-oriented systems. Indeed, research on
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7 several atypical groups, including children with ADHD, CD or problems of substance
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9 abuse, also highlights this interplay between top-down and bottom-up processes. Although
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11 not yet evident in research on autism, it is worth noting that the amygdala, which is a key
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13 substrate involved in reward processing, is central to at least one prominent account of
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15 autism (Baron-Cohen et al., 2000). Thus extending this dual focus on EF and reward
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17 processing to children with autism would appear a fruitful direction for future research.
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22 A second notable developmental continuity is that, across a wide age range,
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24 typically developing individuals with good EF are more likely than their peers to do well
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26 on tests of theory of mind and show positive self-concepts, and are less likely than their
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28 peers to display antisocial behaviors. Perhaps related to these stable correlates of EF,
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30 longitudinal studies support EF as a predictor of later academic achievement in both young
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32 children and adolescents. Finally, across a wide variety of ages, at least some aspects of EF
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34 (e.g., working memory) appear malleable to training effects.
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39 Examples of age-related contrasts include differences in the nature of EF:
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41 improvements in some aspects of EF (such as inhibitory control) can be seen from a very
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43 early age, while other aspects (e.g., planning) do not show marked improvements until
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45 much later on in development. Another important contrast concerns the extent to which EF
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47 can be associated with a localized neural base: age-related improvements in EF appear
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49 hand in hand with increased fronto-striatal activation, such that development is
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51 characterized by a progression from diffuse to specific neural substrate. Several age-related
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53 functional changes in children's performance on EF tasks suggest that this progressive
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3 localization of neural substrate may reflect increases in how strategic children and
4 adolescents are when completing EF tasks. For example, adults and children differ
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6 markedly in how they respond to more challenging situations; while adults can reduce their
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8 speed of response to remain accurate, young children typically show a drop in accuracy.
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10 Similarly, young children are particularly likely to show an ‘all or none’ effect, in that they
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12 can inhibit a response if this is consistently required of them, but find it much harder to
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14 cope with situations that place varying demands on this system of inhibitory control.
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16 Finally, related to these contrasts in strategy use, training studies indicate an age-related
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18 contrast in the optimal format of the training tasks, with task variability increasing training
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20 benefits in adults, but reducing training benefits in children.
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27 Together, the above age-related contrasts lead to a third key conclusion; namely
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29 the need to take developmental issues seriously when examining a construct such as EF
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31 that shows such a protracted developmental course. For example, if the differences noted
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33 above do indeed reflect an age-related contrast in strategy use on EF tasks, then the validity
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35 of across-age comparisons is in question, as different sets of skills may well underpin
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37 performance on the same task for children of different ages. An important first step in
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39 addressing this issue is to establish measurement invariance before comparing EF skills
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41 across different age groups (c.f. Hughes et al., 2010). Developmental issues are also raised
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43 by findings from studies of atypical groups. Thus, studies comparing different clinical
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45 groups (e.g., children with autism and children with ADHD) should be designed so that
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47 contrasts in developmental *trajectories* can be elucidated. The few existing studies that
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49 adopt a developmental perspective indicate that children with autism may show greater
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51 progress than children with ADHD, but the reasons for this are not yet known.
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3 The final conclusions to emerge from this review concern the interplay between
4 EF and children's environments. First, although individual differences in EF have been
5 viewed as almost entirely genetic in origin (e.g., Friedman et al., 2008), there is growing
6 evidence that, for young children at least, environmental influences can be substantial.
7 Thus, detailed longitudinal studies highlight the importance of family factors (e.g.,
8 maternal wellbeing, sensitivity and consistency of parenting). In addition, at least three
9 randomized control trials show that early educational interventions have positive effects on
10 EF, which may be: (i) strongest for children with low levels of EF (i.e., EF moderates the
11 impact of interventions); (ii) pivotal to explaining the substantial improvement in children's
12 behavior as a result of such interventions (i.e., EF is a mediator of intervention effects); and
13 (iii) achieved indirectly, via improvements in children's theory-of-mind skills. Clearly then,
14 tracing the mechanisms that underpin associations between family environments and
15 children's growing EF skills, and between interventions and children's social and cognitive
16 achievements are important challenges for future research. The stage is set for another very
17 productive 20 years of research into children's developing EF skills!
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