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Executive function in the first three years of life:

precursors, predictors and patterns

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Abstract

Executive function (EF) underpins the ability to set goals and work towards those goals by co-ordinating thought and action. Its emergence during the first 3 years of life is under-studied, largely due to the limitations that early social, motor and language skills place on performance on traditional EF tasks. Nevertheless, across the fields of cognitive psychology, neuroscience, social development and temperament research, evidence is amassing of meaningful precursors and predictors of EF. This review draws together the evidence, highlighting methodological considerations and areas of theoretical debate, and identifies 4 domains critical to the development of EF: control of attention, self-regulation, processing speed and cognitive flexibility. Individual differences within these domains have clinical significance both in terms of the identification of risk markers for later executive dysfunction and for the target or delivery of early intervention to ameliorate this risk. By the end of the third year, typically-developing infants are able to selectively employ impulse control and cognitive flexibility to achieve goal-directed responses to novel situations.

Keywords

Executive function, cognitive development, infancy, regulation, attention, effortful control

What is Executive Function and Why is it Important?

Executive function (EF) can be described as the cognitive toolkit of success. It underpins the ability to set goals and work towards those goals by co-ordinating thought and action, particularly in new situations. The precise nature of the 'tools' in the 'kit' is a matter of considerable debate, but they are largely considered to be higher-order self-regulatory processes, including the control of attention and motor responses, resistance to interference, and delay of gratification (Carlson, Mandell & Williams, 2004; Diamond, 2013; Jurado & Rosselli, 2007), or, as Barkley puts it "those self-directed actions needed to choose goals and to create, enact, and sustain actions toward those goals"(Barkley, 2012, p. 60).

From its emergence in very early childhood through to its decline in late adulthood, EF supports and constrains an individual's ability to learn and thrive across their lifespan (Diamond, 2013). Not only does early EF have strong links to children's later social and academic functioning (Blair & Peters Razza, 2007; Eisenberg et al., 2009) but difficulties with some EFs are implicated in a range of disorders including Attention Deficit Hyperactivity Disorder (ADHD) and Autism Spectrum Disorder (ASD) (Barkley, 1997; Ozonoff, Pennington & Rogers, 1991; Rommelse, Geurts, Franke, Buitelaar & Hartman, 2011). However, currently executive dysfunction is primarily detected during a child's school years. By developing our understanding of the developmental pathway(s) involved in EF we may be able to monitor and intervene in cases where emergent EF is delayed or disrupted, whilst the brain is most responsive to treatment (Johnson, 2012; Wass, 2015).

Goals and Structure of This Review

The main aim of this review is to present an account of the current status of understanding of early EF and its components, by drawing together evidence of domains

foundational to EF, the related attributes and skills which have predictive validity to EF later in life, and EF skills which emerge in the first 3 years of life. In doing so, this review outlines and critiques key methods used to measure EF and related attributes prior to the age of 3 and highlights gaps in knowledge and areas of theoretical and empirical debate.

The EF-related processes identified in this review can be categorised as relating broadly to one of four domains: control of attention, self-regulation and reactivity, processing speed and cognitive flexibility. These processes are each relevant to EF first as a foundational component – both supporting the development of EF itself, and driving individual differences in that development – and then subsequently as a directly-contributing component of EF performance. As shall be demonstrated, these processes are deeply inter-related throughout early development.

In adults, performance on EF tasks has been found to be driven by a Common EF factor and separate 'Updating-specific' and 'Shifting-specific' factors (Miyake & Friedman, 2012). Common EF is understood to be the ability that allows individuals to maintain task-relevant goals, which in turn influences which other skills are deployed, and is isomorphic to the variable previously labelled in models as Inhibitory Control (the ability to deliberately override dominant or prepotent responses) (Miyake, Emerson & Friedman, 2000). Thus, in adults, EF has both unity and diversity. In early childhood a dissociable pattern of EF abilities is less clearly evident. Many researchers have found that a single latent EF construct best describes preschoolers' performance on EF batteries (Hughes, Ensor, Wilson, & Graham, 2009; Senn, Espy & Kaufmann, 2004; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011; Willoughby, Wirth, Blair & Family Life Project Investigators, 2012) – although more recent studies have detected dissociable EF factors in children aged 2 and 3 (Bernier, Carlson, Deschênes & Matte-Gagné, 2012; Garon, Smith, & Bryson, 2014; Mulder, Hoofs, Verhagen,

van der Veen & Leseman, 2014; Skogan et al. 2015). In this review, concurrent or predictive

relations to probable latent variables are drawn out where supporting evidence is available.

Figure 1 illustrates a conceptual model of the relationships between the foundational

domains identified in infancy, emerging and dissociable EFs observed in toddlerhood, and

their predictive relationship to the 3 EF factors observed (by some) from preschool and

beyond. This model has been developed by drawing together the evidence currently available,

but remains to be tested with a longitudinal data set comprising all the relevant measures.

[Insert Figure 1 here]

Figure 1. Conceptual model of the development of EF. Elements labelled in bold are

proposed as latent factors of emergent EF.

In sum, the evidence presented in this review suggests that in the first 3 years of life

skills related to each of the latent variables driving adult EF performance develop, and can be

captured via laboratory or parent report measures of effortful control. Whilst the line between

effortful control and EF is blurred, in this review effortful control is taken to refer to the

deliberate control of behaviour and attention, which may be stimulus-driven or adult-directed

(Kochanska, Murray & Harlan, 2000; Rothbart, 1989). EF, meanwhile, denotes a more

independent, flexible and goal-directed response to novel situations (Blair & Peters Razza,

2007). The transition from effortful control to EF is gradual and appears to occur over the

course of the third year of life (Bullock & Lütkenhaus, 1988). Indeed, Kagan (1981) has

suggested that the hallmark of the end of the second year is the emergence of an active, goal-

directed self: this review aims to present how developments in control of attention, self-

regulation, processing speed and cognitive flexibility make this transition possible.

Measuring Emergent EF

Whilst there has been considerable examination of EF in pre-schoolers (Garon, Bryson & Smith, 2008; Isquith, Gioia, & Espy, 2004; Wiebe, 2014) until recently the role and emergence of EF prior to this had been largely under studied. This is in part due to the difficulty in measuring emergent (by which is meant still-developing, and not yet stable) EF during a period of significant development in social, motor and language skills (Isquith et al., 2004) – a particular problem given the difficulty in establishing 'pure' measures of EF (i.e. which aren't in fact also measuring non-executive processes) (Burgess, 1997; Miyake & Friedman, 2012). For example, not only do EF tasks that require verbal comprehension carry the risk of toddlers misunderstanding the task requirements, but by taxing their verbal comprehension researchers place an additional cognitive load on the child, which may influence performance (Hughes & Graham, 2002). Furthermore, internally-generated language appears itself to play a role in EF, both as a means of regulation and through strengthening representations in working memory, meaning that language skills may influence performance even when instructions are entirely non-verbal (Barkley, 1997; Miller & Marcovitch, 2011; Zelazo, 2015).

Nevertheless, over the past 15 years, a number of researchers have attempted to tackle the 'terrible twos' by developing measures of EF appropriate for this particular age group (Blakey, Visser & Carroll, 2016; Carlson, 2005; Garon et al., 2014; Hughes & Ensor, 2005; Kochanska et al., 2000; Mulder et al., 2014). Many of these studies have employed batteries of tasks to attempt to overcome the task-impurity problem mentioned above and it has been demonstrated that latent factors modelled from a battery, rather than individual task performance, show greater agreements across different informant ratings and greater test-retest reliability (Willoughby, Blair, Wirth & Greenberg, 2010). At the same time an

increasing emphasis on longitudinal development from infancy has demonstrated that some

individual differences in cognition and behaviour can be tracked back to the first few months

of life (Bornstein, 2014), making this a timely point at which to review what we now know

about precursors, predictors and patterns of EF in the first 3 years of life.

In the interests of generalisability, where possible this review focuses on evidence

from studies of typically-developing populations, and unless stated otherwise it should be

assumed that the participants in the studies described were typically developing. However, in

some cases, studies with non-typical populations such as preterm infants have revealed

interesting issues that have not yet been followed up with a typically-developing sample.

Preterm infants (particularly those with extremely low birth weight) are a particularly

relevant group as they are known to be at risk for problems with EF in later childhood

(Anderson & Doyle, 2004; Mulder, Pitchford, Hagger & Marlow, 2009) – however we

should be wary of making inferences from these populations about typical EF development

without further study, particularly given the susceptibility of performance on EF tasks to

interactions with other aspects known to be atypical amongst preterm infants, such as the

early environment and motor skills (Bracewell & Marlow, 2002; Siegel, 1984).

Domains Linked to Emergent EF

Control of Attention

Focus of discussion and key definitions.

Infants are selective in their attention from the first day of life, but make huge leaps in

their ability to direct and sustain this selectivity over the first year (Ruff & Rothbart, 1996). It

has been argued that these developments form the foundation for self-regulation and

cognitive flexibility (both themselves key domains relating to emergent EF), and may be the

source of common variance in performance across EF tasks (Garon et al, 2008). The evidence

presented in this section will demonstrate that this control of attention begins to emerge as early as 4 months, but undergoes a significant transition at around 9 months, from which point individual differences in control of attention show moderate concurrent correlation and some predictive validity to measures of impulse control and cognitive flexibility within the third year of life. Possible reasons for the limited predictive relationship of infant attentional control to measures of more mature EF are discussed, both in terms of measurement issues and the moderating effects of parenting.

Early individual differences in control of attention, and their relationship to EF.

In the first 6 months of life attention is highly influenced by novelty of objects and events, and infants tend to have difficulty disengaging from highly novel or salient stimuli (known as 'sticky' or 'obligatory attention'). Thus one of the earliest forms of attentional control, emerging at around 4 months, is the ability to shift the 'spotlight' of attention focus and thus exert rudimentary selective attention (Johnson, Posner & Rothbart, 1991). This ability is thought to utilise the orienting system of attention (see Box 1).

Two paradigms have been developed to study this emerging skill: the 'Fixation Shift' and 'Gap-Overlap' tasks. Both tasks compare an infant's ability to make a shift when a central target disappears as or before a peripheral target appears (non-competition condition – considered to be a measure of oculomotor efficiency or processing speed) with the ability to shift fixation when the central target remains visible during the appearance of the peripheral target (competition condition – considered to be a measure of both oculomotor efficiency and attentional orienting) (Atkinson, Hood, Wattam-Bell & Braddick, 1992; Csibra, Tucker, Johnson, 1998; Elison, et al. 2013). During the first 3 to 4 months of infancy, latencies to shift are commonly considerably longer in the competition than non-competition conditions, a difference that reduces with age. This difference between non-/competition conditions has

been found to reduce at a slower rate in preterm infants (Atkinson et al., 1992; Atkinson et al., 2008).

Ease of disengagement within the Gap-Overlap task at around 6 months is associated with concurrent parental reports of greater soothability and lower distress levels (McConnell & Bryson, 2005). This is compatible with the suggestion that a rudimentary form of self-regulation, drawing on the ability to control attention, is evident by 6 months (Rothbart & Ahadi, 1994). Interestingly however, whilst at 12 months easier disengagement is still associated with high concurrent regulation scores, by 18 and 24 months this pattern has reversed. It has been suggested that during infancy, when mainly the orienting network (with its high novelty preference – see Box 1) is involved, high levels of control mean faster saccades to novel peripheral events. In later infancy, the time to initiate a saccade depends upon how strongly attention is engaged with the central stimulus; hence, colourful and changing central stimuli lead to a high level of engagement and those with high levels of control process the central event more strongly and thus more slowly initiate saccades to the periphery; i.e. they show reduced distractibility (Nakagawa and Sukigara, 2013).

Indeed, the counter skill to disengagement, and an alternative aspect of early selective spatial attention, is the ability to inhibit orientation to peripheral distractors. This ability, commonly referred to as focussed or sustained attention, is thought to relate to the alerting system (see Box 1). In infants it can be measured by the 'Freeze-frame' task (Holmboe, Fearon, Csibra, Tucker & Johnson, 2008). In this task, an engaging central animation stimulus is displayed, but briefly frozen if the infant looks to peripheral distractors. Nine-month-old infants' ability to inhibit looks to distractors in this task is positively correlated with performance on an A-not-B task (an early EF-like task, described in the section on Cognitive Flexibility). Holmboe et al. (2008) also found that a subset of 9-month-olds

showed a difference in levels of inhibition to distractors during trials where the central animation changed versus trials where the central animation stayed the same; thereby demonstrating more sophisticated selectivity on the basis of perceptual features. Moreover, the subset of infants that showed selective inhibition during the 'Freeze-frame' tended to show less interference at 24 months on the Spatial Conflict task; a more demanding selective attention task which also requires resolution of conflict (see Cognitive Flexibility section) and is therefore considered to be an early measure of EF (Holmboe et al., 2008). Overall, this pattern of results indicates both that control over selective attention is undergoing significant development at around 9 months – most likely related to the increasing dominance of the executive attention network over the orienting system (see Box 1) – and that individual differences in selective attention at this age have predictive value to performance on EF tasks at 2 years.

Supporting evidence for a transitional phase in the development of the control of attention at around 9 months comes from a study using 2 tasks as measures of attentional control: a free-play paradigm (in which infants were given multiple age-appropriate toys and the duration of focused attention was calculated – see the section on Measuring Focused Attention) and a peripheral distractor paradigm (in which infants were presented with a colourful multipart toy during a familiarisation period, after which coloured blinking rectangles accompanied by beeping were presented in the periphery and infants' latency to turn to the distractor was recorded) (Kannas, Oakes & Shaddy, 2006). Whereas attention measures were correlated across tasks for 31-month-olds, they were not for 7- or 9-month-olds. Additionally, attention was stable from 7 to 9 months and from 9 to 31 months, indicating a period of transition at around 9 months during which attention systems become more unified.

When focused attention is used an index of attentional control from 9 months of age, the relationship with self-regulation observed above continues. For example, the duration of 9-month-olds' focused attention during a free play task predicts performance on an effortful control battery (see section on Measuring Effortful Control) at 22 months (Kochanska et al. 2000). Furthermore, Johansson, Marciszko, Gredebäck, Nyström and Bohlin (2015) found that levels of focused attention aged 12 months predicted both differences in effortful control (as reported by parents) and performance in an A-not-B task aged 25 months, supporting links between attentional control and both self-regulation and cognitive flexibility.

However, whilst the relationship between concurrent attentional control and self-regulation appears to extend into the third year of life and beyond (Carlson, Mandell & Williams, 2004; Gerardi-Caulton, 2000; Peake, Hebl, & Mischel, 2002; Putnam, Spritz, & Stifter, 2002) the predictive validity of individual differences in infant attentional control to EF past the 2-year stage is less clear. For example, Kochanska et al. (2000) found that the predictive relationship between 9-month-olds' focused attention and later effortful control did not extend to 33 months. One possible, but untested, explanation for this is that by 33 months emergent EF abilities are driven by two dissociable latent factors, only one of which (cognitive flexiblity) is directly related to individual differences in control of attention in infancy (see Figure 1); a composite measure of effortful control comprising both factors might mask this relationship. This explanation is partially supported by the finding that 12-month-olds' levels of sustained attention are associated with their performance on an updating task (see Cognitive Flexibility section) at age 3 (Johansson, Marciszko, Brocki & Bohlin, 2015). However, it is somewhat undermined by the finding, from the same study, that infant attention levels did not predict 3-year-old performance on conflict tasks – also considered measures of cognitive flexibilty.

In addition, it appears that individual differences in control of attention show only moderate stability across the second year of life (Choudhury & Gorman, 2000; Gaertner, Spinrad & Eisenberg, 2008; Putnam, Gartstein & Rothbart, 2006; Power, Chapieski & McGrath, 1985, Ruff et al., 1990). This limited stability may be caused by methodological issues in the measurement of attentional control (see the section below on Measuring focused attention) and/or the moderating effect of environmental and temperament factors.

Moderating and mediating factors.

Researchers are increasingly recognising the influence of environmental factors in the development of early EF, particularly in terms of the impact of early relational experiences (Bernier et al., 2012; Bridgett et al., 2011; Blair, 2016, Fay-Stammbach, Hawes & Meredith, 2014). In particular, the early caregiving environment has been demonstrated to show significant impact on developing attentional control (Gaertner et al. 2008; Graziano, Calkins and Keane 2011; Kochanska et al.,2000). For example, Bono and Stifter (2003) found that children of mothers who consistently used attention-maintenance strategies during free-play sessions showed higher focused attention at 18 months, and higher scores on a test of cognitive function, whilst children of mothers who frequently used redirecting strategies showed poorer focused attention and lower cognitive scores at the same age.

Environmental factors are likely to be reciprocal, cumulative and in turn influenced by other variables which change over time, making systematic study difficult and reducing the likelihood of finding clear long-term predictive relationships (Johnson, 2011; Thelen, 1990). Indeed, even the effect of parental-maintenance/redirecting strategies is context specific; in contexts where children are not distressed, attention redirection can be intrusive and linked to reduced focused attention as described above, but in contexts where regulation is required, in order to reduce distress and to delay gratification, redirection is often adaptive

(Rothbart, Ziaie, & O'Boyle, 1992; Stifter & Braungart, 1995). Indeed, levels of negative emotionality and poor attention appear to have an interactive relationship in the early development of cognitive and behavioural function (Lawson & Ruff, 2004). These issues are discussed further in the next section on Self-Regulation and Reactivity.

[Method Pull-out A] Measuring focused attention.

As indicated above, selective sustained attention in infancy is commonly operationalised in behavioural terms as focused attention: attention maintained on an object, event or task for the purpose of learning more about it and/or reaching a goal (Ruff, 1990). Focused attention is characterised by a reduction of heart rate, intense facial expression, minimal body movement and resistance to distractors (Lansink, Mintz, & Richards, 2000; Oakes, Ross-Sheehy, & Kannass, 2004; Richards, 1989; Ruff & Capozzoli, 2003) and can be contrasted with casual attention, which is characterised by engagement with stimuli in a repetitive and unfocused manner during which little to no information regarding the stimulus is processed (Oakes & Tellinghuisen, 1994).

Laboratory observations have demonstrated only moderate stability in individual differences in focused attention between tasks and across the second year of life (Choudhury & Gorman, 2000; Gaertner et al., 2008; Power et al., 1985). One reason for this is that researchers often attempt to capture it within free play settings, in which behaviour is not always goal-directed. Indeed, since every situation has a unique physical, social and cognitive context it may sometimes be adaptive for the child to engage in non-goal-directed regulatory behaviours such as self-soothing if over-aroused or resting if tired (Ruff & Rothbart, 1996; Ruff, Lawson, Parrinello, & Weissberg, 1990). Designing focused attention paradigms with a clear age-appropriate goal, and ensuring a calm baseline state, is therefore critical to increasing the likelihood of capturing individual differences in focused attention rather than

differences in arousal or regulation (Ruff et al., 1990). The Laboratory Temperament Assessment Battery provides examples of well-constructed tasks and coding schemes that can be used in the laboratory or home setting to capture focused attention as well as other indices of individual differences (Gagne, Van Hulle, Aksan, Essex & Goldsmith, 2011; Goldsmith & Rothbart, 1992; Goldsmith, Reilly, Lemery, Longley, & Prescott, 1993).

An alternative approach to avoiding context-specific fluctuations is to use parental or caregiver report. This method takes advantage of caregivers' extensive opportunities to observe young children across a broad array of contexts, providing a cost- and time-effective insight into infant behaviour that is both broad and deep (Rothbart & Maruo, 1990). Whilst cautions about the reliability of parental report have been noted – particularly with regards to the potential for bias due to the influence of social desirability, limited accuracy of memories of events, and unfamiliarity with the typical ranges of infant behaviour – these concerns can be at least partially addressed by asking about only recently-occurring events and concrete infant behaviours rather than requiring the parents to make abstract or comparative judgments (Rothbart & Goldsmith, 1985). Such an approach is taken by The Infant Behavior Questionnaire-Revised (IBQ-R) (Gartstein & Rothbart, 2003) for 3-to-12-month-olds and the Early Childhood Behavior Questionnaire (ECBQ) (Putnam et al., 2006) for 18- to-36-month-olds; two of the best-established caregiver report measures of early temperament. Within these multiple-scale measures the most pertinent to control of attention is the Duration of Orienting scale in the IBQ-R and the Attention Focusing scale of the ECBQ.

Agreement between parental report and laboratory measures of attention is moderate: for example, parental report of 13.5-month-olds' duration of orienting positively correlates with the length of sustained play observed in the laboratory (Rothbart, Derryberry & Hershey, 2000). However, the longitudinal stability between infant and toddler parent report

measures of attention is more limited, given that the Duration of Orienting scale has low predictive validity to the ECBQ Attention Focusing scale (Gartstein, Putnam, Becken-Jones & Rothbart, 2002). The authors note that this is to be expected, given the considerable development that the attention systems undergo within the first year of life. Indeed, younger infants score higher for Duration of Orienting compared with older infants within the IBQ-R, a trend that is reversed in the equivalent Attention Focusing scale of the ECBQ (Putnam et al., 2006) and which suggests the measures are tapping two different constructs prior to and after the shift towards endogenous attention that occurs at around 9 months. Moreover, whilst in older infants shifting may reflect a particular attentional style or strategy, in younger infants differences in average looking duration may be more influenced by speed of information processing (Colombo & Cheatham, 2006) – as explored in more detail in the Processing Speed section of this review. Additionally, however, the way that the Duration of Orienting scale is operationalised potentially conflates strengths in sustaining attention with difficulties with disengagement. For example, a child who frequently "plays with one toy or object for 10 minutes or longer" or "stares at a mobile, crib bumper or picture for 5 minutes or longer" may be demonstrating the ability to maintain concentration in the context of cognitive and social demands (selective sustained attention) or may be showing rigid and repetitive behaviours linked to a difficulty in re-orienting. The questionnaire authors' note that an Attentional Shifting scale (capturing the ability to transfer attentional focus from one activity or task to another) was not retained in the IBQ-R because an operational definition for this scale could not be established independent of Duration of Orienting supports this observation (Gartstein & Rothbart, 2003). This may be a particular issue for use of the IBQ-R in assessment of sustained attention within populations at-risk for problems with re-orienting attention, such as infants at high-risk for ASD (Holmboe et al., 2010).

Meanwhile Attention Focusing scores in the ECBQ show moderate longitudinal stability across a 6- to 12-month timespan when completed by primary caregivers but not secondary caregivers, whilst mother and non-parental caregiver reports of attention focusing are correlated at fairly low levels at 18 months and are unrelated at 30 months (Putnam et al., 2006; Gaertner, et al., 2008). One reason for this lack of agreement is that non-parental caregivers have more varying reference points from which to judge individual children's attentional skills than parents, particularly once the child is in a group childcare setting. Further research is required to validate both types of caregiver report against laboratory measures of control of attention and to establish the predictive validity of each type of report.

[Box 1] Attention systems.

Much of the work on EF in adults and older children assumes a central role of a functional-structural mapping known as the executive attention network. Executive attention is one of 3 networks proposed by Posner and colleagues whereby the alerting system maintains sensitivity to incoming information (sustained attention), the orienting system drives the ability to respond to certain types of input and ignore others (selective attention) and to shift between targets, and the executive attention network exerts top-down volitional control and recruits resources necessary for goal-directed behaviour, error detection and conflict resolution (Petersen & Posner, 2012; Posner & Petersen, 1990).

Contemporary evidence suggests that the executive attention network is in fact best conceived as 2 separable networks – one 'control system' related to the maintenance of task set, and one related to moment-to-moment performance feedback, task switching and conflict resolution (see Cognitive Flexibility section) (Dosenbach et al., 2008). However, these likely operate in close interaction throughout development, and may have a common origin (Petersen & Posner, 2012). Specifically, it appears that during infancy attentional control

depends primarily on the orienting network – as described in the section on Self-Regulation and Reactivity (Posner, Rothbart, Sheese & Voelker, 2012; Rothbart, Sheese, Rueda & Posner, 2011). By the end of the first year an early form of executive attention is at least partially active however, and over the following 12 months it takes dominance over the other attention networks in a range of domains, including visual orienting, motor behaviour and self-regulation (Posner et al., 2012).

Self-Regulation and Reactivity

      Focus of discussion and key definitions.

Much of the work on very early development of EF is drawn from the temperament literature, which investigates individual differences in basic psychological processes of emotion, motivation and attention. These differences are considered to be influenced by genetic inheritance, maturation and experience (Rothbart & Bates; 1998; Posner & Rothbart, 1998). More specifically, temperament has been defined as individual differences in reactivity and self-regulation (Rothbart & Bates, 2006).

      Reactivity entails an individual's response to a stimulus change or alteration in the environment, which is manifested in changes in behaviour and/or the physiological systems (Derryberry & Rothbart, 2001; Propper & Moore, 2006). At a behavioural level, reactivity can be observed in terms of a range of responses (e.g. negative affect, fear, approach, motor activity) which in infancy have been characterised primarily in terms of two dimensions or factors: Negative Affectivity and Extraversion/Surgency (Gartstein & Rothbart, 2003; Rothbart, 1981).

Self-regulation refers to the set of processes used to modulate this reactivity (Eisenberg, Hofer & Vaughan, 2007; Ruff & Rothbart, 1996; Rothbart & Posner, 1985). As will be demonstrated below, self-regulation is both a foundational component in the development of EF, but is also, via its relationship to inhibitory control, closely linked to Common EF, one of the 3 latent variables found to drive EF performance in older children and adults (Garon et al, 2014; Miyake & Friedman, 2012). Thus this section maps both the role of self-regulation in early EF development and its emergence as a measurable component of EF tasks.

It has been proposed that the lower-order regulatory processes developing in the first year of life to moderate reactivity responses provide a framework for later more complex forms of self-regulation, so that strong avoidance and self-soothing strategies will precede strong effortful control capacities (Blair & Peters Razza, 2007; Kopp, 1982). The evidence presented below confirms that individual differences in self-regulation emerge as early as 8 months of age, and have predictive validity to later EF from the second year of life. The research presented also demonstrates that individual differences in self-regulation emerge in interaction with biologically-driven differences in reactivity and sex, and that this relationship can be moderated by environmental factors such as parenting.

Early individual differences in reactivity and self-regulation, and their relationship to EF.

Self-regulation is a recursive system, involving both volitional 'top-down' control, and non-volitional 'bottom-up' processes (Blair, 2016). In infancy, this system is focused on regulation of the stress response, emotion and attention (i.e. reactivity), and is almost exclusively non-volitional. For example, emotional responses to novel or aversive stimuli are modulated by self-comforting (e.g. thumb or finger sucking) and by orienting (e.g. looking

away from distressing stimuli to reduce negative affect). Whilst initially this is at least partially contingent on caregiver actions (i.e. an adult providing the means of distraction or supplying the pacifier), by 5 months infants are capable of self-regulation through these means (Rothbart, Sheese, Rueda & Posner, 2011; Stifter & Braungart, 1995).

As the child develops, regulation becomes more under conscious control and can be applied not only to regulation of the internal self but also to the deliberate control of behaviour (Derryberry & Rothbart, 2001) – as indexed by laboratory measures of effortful control (see section on Measuring Effortful Control). By 22 months, toddlers are able to inhibit behaviour the majority of the time upon parental instruction (Kochanska, 2002).

Critically to the development of EF, even whilst self-regulation is very much 'under construction' during infancy, it shows stability in terms of prediction of individual differences over time. For example, individual differences in impulse control tasks at 8 months (for example complying with parental instruction to not touch an object) predict performance on similar tasks at 13-15 months (Kochanska, Tjebkes, & Forman, 1998), whilst at 15 months, use of regulatory behaviours (avoidance and self-soothing) in the presence of emotional reactivity predict EF levels at age 4 (Ursache, Blair, Stifter, Voegtline, & Family Life Project, 2013). By 22 months, performance on a battery of effortful control tasks predicts 33-month effortful control scores (Kochanska, et al., 2000), and shows longitudinal stability to 66 months (Kochanska, Murray & Coy, 1997). Furthermore, the ability to hold off touching a prohibited toy at 12 months predicts working memory performance at 36 months (Johansson, Marciszko, Brocki, & Bohlin, 2015) and at 14 months predicts high Common EF at age 17 (Friedman, Miyake, Robinson & Hewitt, 2011). Interestingly, whilst highly-restrained infants showed higher Common EF at age 17 they showed poorer Shifting-specific performance compared to the less-restrained group, and similar performance in Updating-

specific abilities (Friedman et al., 2011). This pattern of evidence suggests that whilst in early development impulse control is closely related to working memory performance, the relationship between infant impulse control and adolescent EF pertains only to Common EF.

A similar pattern of evidence relating early self-regulation to later EF emerges from temperament studies based on parent report, with the ECBQ factor Effortful Control at 18-32 months predictive of Effortful Control at age 4. Moreover, whilst Effortful Control is conventionally only measured as a dimension of temperament from 18 months (see section on Measuring Effortful control), there is a strong relationship between scores on this factor, and parent report of infant regulatory capacity, as indexed by the Regulatory Capacity/Orienting factor (Putnam, Rothbart, & Gartstein, 2008). For example, composite scores from the Cuddliness and Duration of Orienting scales at 8-13 months are associated with levels of Effortful Control at 20-25 months of age (Casalin, Luyten, Vliegen,& Meurs, 2012).

In turn, self-regulation develops in interaction with and in response to, reactivity, making this an important aspect in the early development of EF. For example, it is argued that highly reactive infants who become extremely distressed in response to stimulation become so disrupted they are unable to develop the internal mechanisms necessary for self-regulation (Fox & Calkins, 1993); so much so that children's negative reactivity has been identified as a risk factor for poor-regulation (Allhusen et al., 2004; Raikes, Robinson, Bradley, Raikes, & Ayoub, 2007; Rothbart & Bates, 1998). Inversely, positive affectivity may be a protective factor; infant scores on the High-Intensity Pleasure, Smiling and Laughter and Positive Anticipation scales of the IBQ have all been shown to predict toddler and/or preschool Effortful Control scores (Casalin et al., 2012; Komsi et al., 2006; Putnam et al., 2008).

The relationship between infant affect and toddler effortful control may in turn be moderated by infant activity level. A cluster analysis of 231 children identified three temperament 'types' based on temperament scale scores collected at 6 months and 66 months of age. These were 'resilient', 'under-controlled' and 'over-controlled'. Of note, both the resilient and over-controlled types scored highly for the Effortful Control factor at age 5½, but showed major differences on other measures: the resilient type was characterised by high activity level and high positive affectivity/low negative affectivity in infancy, whereas the over-controlled type had moderate levels of both positive and negative affectivity, but low activity level scores. Furthermore, the third type – 'under-controlled' – who showed high activity level but low positive affectivity/high negative affectivity, went on to demonstrate low effortful control in middle childhood (Komsi et al., 2006). This pattern corroborates other findings that negative emotionality and poor attention have an interactive relationship as risk factors in early development (Lawson & Ruff, 2004). Moreover, it indicates that affect and activity level – which in combination comprise the reactivity component of temperament – interact to predict effortful control, giving rise to two alternative 'pathways' to development of high effortful control (Komsi et al., 2006).

Moderating and mediating factors.

As in all aspects of development, the existence of probabilistic pathways does not imply biological determinism (Nelson & Bloom, 1997), and researchers have long recognised the role of the early environment in moderating the predictive relationship between reactivity and effortful control (Fox, 1994; Propper & Moore, 2006). For example, it is argued that secure attachments enable parents to act as external regulators of their infant's stress response, emotion and attention, which in turn facilitates the child's increasing capacity to self-regulate (e.g., Grossmann & Grossmann, 1991; Propper & Moore, 2006; Spangler, Schieche, Ilg, Maier, & Ackermann, 1994). This has been demonstrated empirically, with the

consistent finding that children who experience greater attunement and positive guidance in early-years interactions with their mothers have better self-regulatory abilities (Calkins, Smih, Gill & Johnson, 1998; Crockenberg & Leerkes, 2004; Conway et al., 2014; Jennings et al., 2008). It is also implicit within temperament measures of infant regulatory capacity; of the 4 scales loading onto the Regulatory Capacity/Orienting factor of the IBQ, 2 in particular – Soothability and Cuddliness – position infant temperament within a dyadic relationship with the 'soother/cuddler', i.e. parent. Thus self-regulation is both a response to, and influenced by, parenting approach (Casalin et al., 2012).

With regards to the specific question of EF development, evidence has shown that responsive parenting during the infant and toddler years correlates both with increased self-regulation and wider EFs (Bernier, Carlson & Whipple, 2010; Bibok, Carpandale & Muller, 2009; Hughes & Ensor 2009; Kochanska, Murray & Harlan, 2000), whilst maternal depression (which has been linked to compromised parent-child interactions, and thus reduced capacity to support the development of infant self-regulation) correlates with lower levels of offspring EF throughout childhood and adolescence (Oettinger & Paulson, 2014; Pearson et al., 2016). Since correlation does not prove causation (Bradley & Bryant, 1983), a number of intervention studies have been implemented to test the nature of this relationship. One such study has demonstrated that maternal sensitivity responsiveness training for mothers of 6-month-old infants with high negative affect leads to improved infant self-regulation at 9 months (van den Boom, 1994). Follow up at 2 and 3-and-a-half years did not specifically assess EF, but general improvements in the intervention condition were noted in problem-solving (which requires integration of multiple EF components, including inhibitory control) (van den Boom, 1995). Others have found that training parents of 2-year-olds in scaffolding, structuring and reasoning to aid their toddler in self-regulation has a positive impact on performance on a battery of effortful control tasks at age 5 (Chang, Shaw, Dishion,

Gardner & Wilson, 2015), and that the positive impacts of parental training extend to broader

EFs at age 6 (Lewis-Morrarty, Dozier, Bernard, Terracciano, & Moore, 2012).

The effects of parenting may be limited to certain "sensitive periods" (Johnson, 2005),

and these may be specific to different facets of EF development. For example, the long-term

links between child attachment security between age 1 and 2 and effortful control (as

measured by an impulse control task) at age 3, are mediated by levels of infant effortful

control and language at age 2; thus the critical period for parenting influence on effortful

control seems to be within the first 2 years of life. In contrast, attachment security and quality

of parent-infant interactions exert influence over cognitive flexibility throughout the toddler

years (Bernier et al., 2012). However, conflicting findings that levels of maternal

responsiveness at 22 months, but not at 9 or 14 months, are related to toddler levels of

effortful control (Kochanska et al. (2000) indicate a need for further longitudinal research

using fine-grained analysis of measures of parenting, effortful control and wider EFs in the

first 3 years of life.

As hinted at by the results of the Bernier et al. (2012) study, one way in which

positive parenting may foster the development of child EF is through providing children with

verbal tools with which to progress from being externally regulated to self-regulated:

Through positive parenting techniques such as scaffolding (the provision of supporting

strategies, including instruction and demonstration), and mind-mindedness (a tendency to use

mental terms while talking to the child) caregivers supply children with the vocabulary to

verbally mediate their own behaviour (Carlson, 2003; Landry, Smith & Swank, 2006).

The role of language as a key mechanism of self-regulation was recognised by

Vygotsky (1962; 1987) and Luria (1959, 1961), who argued that from around the age of 2 to

3 children develop the capacity to use private or self-directed speech to self-regulate. More

recently, Zelazo and colleagues (Zelazo, 2015) have extended this relationship to broader EFs in their Iterative Reprocessing model, whereby language has a core role both in reflection (thereby enabling the elaborative reprocessing of information) and in the formulation and maintenance of goal-specific rules in working memory. This latter role in particular underlines the importance of language for inhibiting inappropriate behavioural responses and selecting appropriate actions (i.e. effortful control).

Empirically, it has been demonstrated that expressive language levels at 24-months correlate with performance on impulse control tasks (see Measuring Effortful Control section) between the age of 24 and 30 months, but not 18 months, even after controlling for age (Vaughn, Krakow, & Kopp, 1984), and predict the trajectory of self-regulation from 24- to 36 months, but not prior to this point (Vallotton & Ayoub, 2011). Additionally, early verbal ability predicts improvements in a broader battery of EF tasks from age 2 to 3 (Hughes & Ensor, 2007). However, it remains to be demonstrated if similar predictive relationships occur earlier in development, thus marking out language as a precursor to EF in its own right.

Meanwhile, the effects of parenting on EF may be in turn be moderated by biologically-driven levels of infant reactivity. Recent studies have shown that whilst self-regulation is more likely to develop within supportive, mutually-responsive parent-child relationships, this is only true for those children exhibiting a high level of emotional reactivity in infancy (Ursache et al. 2013; Kim & Kochanska, 2012). These findings chime with the differential susceptibility hypothesis, which describes how a category of children characterised by high reactivity will thrive in nurturing environments but are more vulnerable in unsupportive contexts (Belsky, 1997; Belsky, Bakermans-Kranenburg & van IJzendoorn, 2007; Boyce & Ellis, 2005). It is proposed that this difference in susceptibility to developmental experiences is driven by alleles of certain genes, most notably 5-HTTLPR and

DRD4 – described as "plasticity genes" because they increase the individual's susceptibility to environmental influences, both for better and for worse (Belsky & Hartman, 2014, p.87). It has been demonstrated that parenting approach measured when an infant is 18 to 21 months old makes a strong difference to levels of impulsivity for children with the 7 repeat allele of the DRD4 gene, but not for those children without this allele, and that this interactive effect is related to parent-reported levels of effortful control at age 4 (Posner et al., 2012).

Sex may also be a moderating factor in the relationship between parenting, reactivity and regulation, with boys consistently found to be more vulnerable to the negative effects of maternal depression than girls (Murray, 1992; Sharp et al., 1995). Even in low-risk environments, in the first 3 years of life boys tend to show higher levels of reactivity than girls, and lower levels of self-regulation (Casalin et al., 2012; Else-Quest, Hyde, Goldsmith, & Van Hulle, 2006; Weinberg, Tronick, & Cohn, 1999). Overall this trend extends into the preschool years (Raikes et al., 2007), and appears to apply also to laboratory measures of general EF, with girls' performance on EF tasks tending to surpass boys' between 26 and 56 months (Carlson et al., 2004; Carlson & Moses, 2001; Kochanska, Murray, Jacques, Koenig & Vandegeest, 1996; Wiebe, Espy & Charak, 2008) – although others have found no gender differences (Garon et al., 2014; Wiebe et al., 2011). Intriguingly, when tasks are differentiated in terms of 'hot' and 'cool' EF (see Box 2), prior to 36 months of age, boys tend to perform better on measures of hot EF than girls (Overman, 2004), despite those tasks presumably particularly requiring regulation of an emotionally-charged response.

The studies above highlight important areas for further investigation in terms of how the relationship between reactivity, self-regulation and EF might be influenced by parenting approach, genetic factors and sex differences. A further under-explored question is how these same relationships might be influenced by individual differences in cognitive ability, such as

early-emerging aptitudes or difficulties with working memory. For example, as discussed in the section below on Cognitive Flexibility, some researchers have suggested that inhibitory control is a behavioural product of working memory (Marcovitch & Zelazo, 1999; Munakata. et al., 2011). Given the strong role of inhibitory control in performance on effortful control tasks (Aksan & Kochanska, 2004), it follows (but is untested) that it might be easier for infants to develop skills in self-regulation if they can hold in mind an external goal or task set from an early age. The following section identifies one possible driver of differences in the ability to identify and hold in mind such information; processing speed.

[Method pull-out B] Measuring effortful control.

As noted in the introduction to this review, effortful control entails the deliberate control of behaviour and attention, which may be stimulus-driven or adult-directed. More specifically it denotes a class of self-regulatory mechanisms relating to the ability to suppress a dominant response in order to perform a subdominant response (Kochanksa et al., 2000; Rothbart, 1989). It can be assessed both through laboratory tasks, and through parent report of temperament.

In the dominant early-years measure of temperament, the ECBQ, Effortful Control is a well-validated factor defined primarily by loadings of Inhibitory Control, Attention Shifting, Low-intensity Pleasure, Cuddliness, and Attention Focusing (Putnam, Gartstein, & Rothbart, 2006). This scale is most closely related (in terms of face validity and predictive relationships) to the IBQ infant temperament factor of Regulatory Capacity/Orienting (RCO) (Putnam, Rothbart, & Gartstein, 2008). The coupling of Duration of Orienting with Regulatory Capacity within the IBQ, and the inclusion of the Attention Focusing scale within the ECBQ acknowledges, on the basis of factor analysis, the important role of attentional

control in the development of self-regulation. However, for studies attempting to unpick causal relationships between the two, this does give rise to a circularity of argument.

Reports of level of agreement between parent-reported Effortful Control scores and laboratory measures of effortful control range from low to moderate for 2- to 3-year-olds, with parent report of inhibitory control showing the strongest relationship with impulse control tasks (Carlson, et al., 2004; Kochanska, 2000, Mulder et al., 2014).

Meanwhile, laboratory measures of effortful control can be loosely categorised into the following groups: impulse control tasks (also known as delay, deferred gratification, self-restraint and inhibitory control tasks) which involve suppressing a dominant response to reach for a desired item until permission has been granted (Aksan & Kochanska, 2004; Friedman et al., 2011; Kochanska et al., 2000; Vaughn, Kopp & Krakow, 1984); compliance tasks, which require participants to engage in typical but mundane activities such as block sorting or cleaning up toys or allowing the researcher to place electrode stickers on them (Stifter, Spinrad & Braungart-Rieker, 1999; Vaughn et al., 1984); motor control tasks such as walking or moving a finger down a line slowly (Kochanska et al., 1996; Kochanska et al., 2000) and effortful attention (Kochanska et al., 2000). Tasks in this final category can also be considered measures of cognitive flexibility, and are therefore discussed in more detail in that section below.

Levels of association between measures of effortful control vary. Some studies have found no relation between performance on conflict, impulse control and compliance tasks at 24 months (Vaughn et al. 1984; Morasch & Bell, 2011), whilst others have found weak correlations between effortful attention and impulse control tasks at 22m (Kochanska et al., 2000) and moderate correlations between those same categories at 24, 30 and 33 m (Carlson et al., 2004; Gerardi-Caulton, 2000; Kochanska et al, 2000). This has led some to conclude

that as children age, the coherence of effortful control activities increases (Kochanska et al.,

2000), perhaps due to increasing stability in an underlying EF factor common to all task types

(i.e. Common EF). However, it may also reflect a reduction with age in variation in levels of

non-EF aspects tapped by the different task types, such as language comprehension or motor

coordination. Alternatively, correlation between effortful control measures may itself be

driven by the common influence of shyness, socialisation and situational factors (such as the

wish to gain rewards and avoid punishment) on performance in these measures as much as

any single underlying regulatory component (Kochanska, Tjebkes & Forman, 1998). Indeed,

as previously noted, the relationship between reactivity and self-regulation is both dynamic

and reciprocal, and for this reason, performance on effortful control measures during the

early years is best understood as the behavioural consequence of the interactive relationship

between individual differences in emotion, motivation, arousal and control of attention. This

interactive relationship makes it difficult to establish the mechanisms underpinning

performance on effortful control tasks: for example, a child scoring high on an impulse

control task may do so because they have high reactive inhibition to novelty (i.e. they are

wary of touching a sweet or toy presented by a relative stranger) or because they have high

capacity to self-regulate the desire to touch the object. Moreover, both trait- (temperament)

and state-levels (induced by the specific properties of the task or general physical state) of

emotion, motivation and arousal will differ between individuals and between tasks

(Willoughby, Holochwost, Blanton & Blair, 2014). For example, performance on impulse

control EF tasks is positively related to sleep regulation in toddlers (Bernier, Carlson,

Bordeleau & Carrier, 2010). In order to unravel these relationships further, studies are

required which combine trait measures of regulatory ability (such as from parent report

questionnaires), batteries of effortful control tasks designed to elicit variance in state (for

example by conducting multiple impulse control tasks using objects that differ in salience, at different points in a testing session), and 'cooler' measures of attentional control (see Box 2).

[Box 2] Hot versus cool EF.

Many researchers make a distinction between 'hot' and 'cool' EFs, where hot tasks are those for which a proximal extrinsic reward or punishment for performance is included, such as impulse control tasks which call for suppressing an emotionally-charged response to a desirable object; and cool tasks which involve more abstract problems such as the selective application of a rule, in which no extrinsic motivator for performance is included (Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Kim, Nordling, Yoon, Boldt & Kochanska, 2013; Metcalfe & Mischel, 1999; Willoughby, Kupersmidt, Voegler-Lee & Bryant, 2011).

Whilst some argue that EF in toddlers and preschoolers is best described by a single factor combining 'hot' and 'cool' dimensions (Allan & Lonigan, 2011; Carlson et al., 2004), Confirmatory Factor Analysis on a large-scale study of 2-year-olds showed that a two-factor hot and cool EF model fitted the data better than a one-factor model (Mulder et al., 2014). The same study demonstrated that performance on cool EF tasks aged 2 predicted both pre-academic skills and behaviour problems at age 3 whilst performance on hot EF tasks predicted behaviour problems only. This relationship appears to strengthen over the preschool years with performance in cool EF tasks predicting academic performance but not behaviour problems and hot EF scores predicting behaviour problems but not academic performance (Di Norcia, Pecora, Bombi, Baumgartner, & Laghi, 2015; Kim et al., 2013; Willoughby et al., 2011).

Increasingly it is recognized that the difference between hot and cool EF is likely to be dimensional to some degree and Zelazo and Cunnigham (2007) have proposed that

problem solving typically involves an interactive relationship between hot and cool EF whereby a rapid emotional response informs a simple approach/avoid response, which is then monitored and refined if necessary on the basis of more abstract if-then rules.

Processing Speed

Focus of discussion and key definitions.

Processing speed entails both rapid assimilation of sensory input and effective encoding strategy. For example, systematic research on infant looking styles has demonstrated that infants who, on average, make shorter glances to novel stimuli both process information more rapidly, and typically encode global features rather than local features (Colombo, Freeseman, Coldren & Frick, 1995; Guy, Reynolds & Zhang, 2013).

In adult populations, speed of processing accounts for much of the variability in performance across a range of EF tasks and is related to all three latent factors: Common EF, Updating and Shifting (Friedman et al., 2008; Kail & Salthouse, 1994; Salthouse, 2011; Salthouse, 2005). This section considers whether processing speed might be part of a developmental cascade influencing EF. The evidence presented will demonstrate that individual differences in processing speed emerge in early infancy, and have predictive validity to EF from 5 months. This relationship appears to pertain primarily to measures of cognitive flexibility.

Early individual differences in processing speed, and their relationship to EF.

Age-related improvements in information processing have been observed from 2 months of age using a variety of measures such as habituation, speed of reactive saccades and looking times (see section on Measuring Processing Speed). For example, habituation studies have documented dramatic improvements in processing speed from 2 to 6 months followed

by gradual levelling off (Colombo, Kapa & Curtindale, 2010; Colombo & Mitchell, 2009) whilst saccadic reaction time studies show a rapid decline in mean reaction time from 2 to 5-6 months, followed by more gradual reductions to 8 months (Canfield et al., 1997). Stability of individual differences in information processing during the first year of life has also been demonstrated (Rose, Feldman & Wallace, 1988; Canfield, Wilken, Schmerl & Smith, 1995).

It has been shown that developmental improvements in processing speed account for age-related improvements in working memory (see Box 3) amongst school-aged children (Kail & Park, 1994; Kail, 2007) and that individual differences in speed have a direct effect on working memory capacity (Fry & Hale, 1996). However, until recently, longitudinal correlates of individual differences in infant information processing were limited to more general cognitive measures such as IQ and academic achievement (Colombo & Mitchell, 2009; Domsch, Lohaus, & Thomas, 2009; Kavšek, 2004). This changed with the work of Rose, Feldman, and Jankowski (2012) who found that differences in processing speed at 7 and 12 months – as measured by ocular reaction times to briefly-presented stimuli and mean look duration (see section on Measuring Processing Speed) – significantly predicted performance on working memory and set-shifting tasks at age 11 years. Moreover, additional analysis suggests that EF is the mediating factor in a cascade of effects in which information processing influences EF, which in turn influences academic achievement ― at least at the level of group differences between preterm infants (who tend to show poor processing speed) and typically-developing infants (Rose, Feldman, & Jankowski, 2011).

Further support for the argument that differences in processing speed drive differences in EF is provided by Cuevas and Bell (2014), who found that infants characterised as short lookers (see section on Measuring Processing Speed) during presentation of a novel stimulus at 5 months exhibited higher composite EF at 24, 36, and 48

months of age (of which half of the 24 month and all the 36 and 48 month tasks could be classed as measures of cognitive flexibility), even after controlling for verbal ability.

Moderating and mediating factors.

Studies of infant information processing have revealed individual differences not only in performance at a given age, but also in growth rate (Canfield et al., 1997). This might be attributable to the effect of moderating factors which exert positive or negative influence over assimilation of sensory input and encoding strategies during early development. For example, differences in processing speed are commonly attributed to organic, structural differences in the central nervous system, so increases in components critical to the structure of neural cell membranes may contribute to improvements in speed. One candidate for such a component is Docosahexaenoic acid (DHA) – a form of long-chain polyunsaturated fatty acids which occurs naturally in human breast milk. Supplementation of infant formula with DHA has been tentatively linked to improved information processing in infants (O'Connor et al., 2001; Willatts & Forsyth, 2000, but see also Auestad et al., 2001); it is therefore feasible that differences in infant diet (for example in the duration of exclusive breastfeeding) might lead to different growth rates in processing speed; although considerable further research is required.

It should also be noted that the predictive value of differences in infant information processing to later EF performance is small, accounting for only 9-19% of variance in the Rose et al. (2012) study. This is likely in part due to the numerous factors that impact EF development and performance across the lifespan (as discussed throughout this review) and in part due to confounding variables in performance on 'EF tasks' such as compliance and comprehension (Hughes & Graham, 2002). Moreover, since no task is a pure measure of the construct of interest, performance on so-called information processing measures may also be

systematically driven by other factors. For example, habituation paradigms tend to rely on the infant preference to look at novel stimuli over stimuli that has already become familiar. This preference might be exerted to a greater or lesser extent depending on individual differences in response to novelty, likely in turn to be driven by individual differences in reactivity and self-regulation, and in control of attention (Berg & Stemberg, 1985).

[Method pull-out C] Measuring processing speed.

Approaches to measuring infant information processing can be broadly split into 2 groups: those that index processing through ocular reaction times (RTs); and those that index processing through looking time to stimuli. In the former category are the baseline conditions of well-established eye-tracking paradigms such as the Gap-Overlap task, in which processing speed is taken to be the RT of a shift to a peripheral stimulus from a central target which disappears as or before a peripheral target appears (Csibra, Tucker, & Johnson, 1998), and the Visual Expectation Paradigm (Canfield et al., 1997; Haith & McCarty, 1990). In the Visual Expectation Paradigm, peripheral stimuli appear randomly on the left or right sides of the infant's visual field. RTs of reactive saccades can be discriminated from anticipatory saccades by frequency analysis: given that anticipatory saccades will not always be accurate they will be significantly more likely to be followed by a corrective saccade, thus the latency bin at which the frequency of corrective saccades abruptly declines corresponds to the minimum reactive saccade RT.

The second approach to measuring infant information processing is through looking time to stimuli. Tasks taking this approach can in turn be broadly divided according to paradigms that use traditional habituation or visual recognition techniques, and those that extract measures of looking time/style from less constrained contexts, such as free-play scenarios. In the first category are fixed-trial habituation procedures in which a visual

stimulus is presented for a fixed time (dependent on the age of the infant). Look duration

during this habituation period can be used as a measure of encoding speed, with shorter looks

indicating more rapid encoding. In the related visual recognition memory paradigm, discrete

stimuli are presented for a fixed duration then followed by a forced-choice novelty preference

task; the proportion of looking time directed at the novel stimulus (novelty-preference score)

indicates the extent to which information about the familiarized stimulus was processed and

encoded in memory (Fagan, Singer, Montie & Shepherd, 1986; Colombo & Mitchell, 2009).

Moderate test-retest reliabilities of novelty-preference scores from variants of the visual

recognition memory paradigm have been reported (Colombo, Mitchell, & Horowitz,

1988; Rose et al., 1988). In the second category, less-constrained 'real-world' variants of this

approach involve presenting infants with three-dimensional visual stimuli (for example a

puppet) until they accrue a set number of looks to the stimulus, then using the median peak

look to classify infants as short lookers or long lookers (Cuevas & Bell, 2014).

Whilst performance on visual expectation and habituation tasks significantly covary

there is also substantial independence between the two measures (Jacobson et al., 1992). It is

likely that some of this independence is caused by the fact that habituation is driven by

perception for object recognition and visual expectation by perception for the guidance of

actions. For example, encoding the details of a visual stimulus is not typically called for in

the Visual Expectation Paradigm, in which the visual images typically appear for less than a

second. Instead, reaction time in this task would seem to reflect more the processes of

detecting peripheral stimuli, deciding what action to take, and triggering the appropriate

response (Canfield et al, 1997). In contrast, habituation studies, which do rely on encoding

for object recognition, enable researchers to evaluate not only speed of assimilation of

sensory input but also processing style: by comparing looking patterns to stimuli that differ in

terms of local (small shapes) and global (overall arrangement) properties, researchers have

been able to ascertain that 'short-looking' infants, who need only about 10s of familiarization time to demonstrate preference for a novel stimulus, begin visual examination by attending to global features then move to local features as exposure duration is increased – a pattern also employed by adults – whilst 'long-looking' infants tend to focus on local elements (Colombo et al., 1995).

Since individual differences in infant processing speed are driven by both (small) differences in speed of assimilation of sensory input and qualitative differences in strategy, as well as differences in perception for the guidance of action and perception for object recognition, both ocular reaction time and habituation-type measures should ideally be used together as complementary indexes of these complementary processes. However, it is as yet unclear whether habituation-type measures can dissociate the influence of processing speed from attentional control once children have developed the ability to exert top-down control over their looking behaviour, from around 9 months.

Cognitive Flexibility

Focus of discussion and key definitions.

When a young child attempts to solve a problem – whether that be how to retrieve the chocolate that their parent has placed just out of reach, or in what particular formation to lay out all of the toys that they possess across the living room floor – they form a mental representation of that problem; the task set. This representation includes the tools or stimuli linked to the goal – the chair on which to climb, the toys which they wish to survey – and the specific rules that they will be adhering to – to reach the chocolate by the fastest means necessary and ignore all distractions, to put toys with wheels in a line and make a pile of everything else. (Meiran, 2010). Formation and maintenance of a task set is thus a foundational requirement for many, if not all, problem-solving/EF tasks (Garon et al., 2014).

As a child progresses towards a goal they may need to update their task set with new task-relevant information and plan their next response accordingly (e.g. the chocolate falls on the floor and they must now climb down from their chair and reach under the table), or to shift to a new task set entirely (e.g. they discover their toy guitar and drum, and decide to create a separate pile of toys which make noise). Both of these mental operations require cognitive flexibility.

In this section it is argued that cognitive flexibility in infants develops through overlapping stages of improvement in *maintaining* task set, *updating* task set, *shifting* task set, and *resolving conflict* within or between task sets. As a construct, cognitive flexibility is closely linked, to that of working memory (see Box 3). However, because in the literature the label 'working memory task' is frequently used purely to refer to updating-type tasks (Blakey et al., 2016, Garon et al., 2014; Hughes & Ensor, 2007), the term cognitive flexibility is used in this section to denote the broader combination of updating/shifting/conflict-resolution type requirements.

In adults through to pre-schoolers, Confirmatory Factor Analysis has demonstrated that cognitive flexibility can be dissociated to 2 separable latent variables – Updating and Shifting – which, alongside Common EF drive EF performance (Garon et al, 2014; Miyake & Friedman, 2012). It has been proposed that Common EF and Updating abilities drive the development of Shifting (Garon et al., 2008; Garon et al, 2014). The evidence presented below suggests that in the first 3 years of life, Updating and Shifting in particular are closely intertwined, dependent as they are on the emerging executive attention network (see Box 1).

Despite considerable cross-sectional research into the development of cognitive flexibility, and the related construct of working memory, there has been little research into stability of individual differences from infancy and beyond. Therefore, the section below

focuses on evidence of the emergence and integration of these abilities. It will be demonstrated that maintaining, updating and shifting abilities all emerge within the first 5 to 8 months of life and that when developmentally-appropriate tasks are used, children as young as 8 months are able to combine these abilities in order to demonstrate (some) cognitive flexibility.

The final aspect of cognitive flexibility – and perhaps the component which differentiates this as a construct from working memory – is the ability to resolve conflict. Studies that have managed to differentiate conflict resolution from simple shifting ability indicate that the ability to resolve conflict emerges gradually in the third year of life. By age 3, the majority of children are able to resolve concurrent conflict, but still struggle with resolving conflict whilst shifting set (Blakey et al, 2016; Carlson et al, 2004; Garon et al, 2014; Johansson, Marciszko, Brocki et al., 2015).

Thus, by the end of the third year of life, each of the core elements of cognitive flexibility are present. However, the ability to combine and control these abilities, such that they might be selectively utilised in more demanding EF tasks, continues to develop slowly from age 3 and beyond.

Maintaining.

A core component of maintaining a task set is the ability to hold something in mind, which requires short-term memory. Developmental research has supported a distinction between phonological and visuospatial short-term memory in adults and children from age 4 (Alloway, Gathercole & Pickering, 2006). However, it is not yet clear if short-term memory can be fractionated before this, and the limited verbal abilities of infants have led to a focus on visuospatial memory.

Evidence from cross-sectional studies investigating visuospatial working memory suggests that short-term memory develops before 6 months, improves dramatically in the second half of the first year, then continues to improve during the first 3 years of life and beyond, both in terms of the length of delay that can be tolerated before the representation decays, and the number of items that can be retained (Gilmore & Johnson, 1995; Kwon, Mee-Kyoung, Luck & Oakes, 2014; Oakes, Baumgartner, Barrett, Messenger & Luck, 2013; Oakes, Hurley, Ross-Sheehy, Luck, 2011; Pelphrey et al., 2004; Reznick, Morrow, Goldman, & Snyder, 2004). By 18 months, infants perform with around 75% accuracy in a task in which an item is placed in 1 of 4 places and must then be retrieved after a 10 second delay, rising to around 85% accuracy at 36 months (Garon et al., 2014).

By the end of the second year of life, infants have developed the ability to maintain more complex task sets. For example, in the Delayed Alternation task the location of a hidden object alternates between 1 of 2 possible positions after each successful trial. Thus to perform well on this task a child must not only hold in mind the previous location, but also the rule that the correct strategy is to look for the objects in the alternate location on the next trial. Performance on the Delayed Alternation task improves reliably with age, from around 50% accuracy with a 10 second delay at age 2, increasing at a rate of 2.44 trials per year from age 2 throughout the preschool years (Espy, Kaufmann, McDiarmid, & Glisky, 1999). Tasks in which the set to be maintained is based on colour and/or shape rather than location show similar trajectories – with 18-month-olds achieving 32% accuracy, 2-year-olds 56% and 3-year-olds approaching 70% – and are thought to tap the same cognitive process. Moreover, maintenance of task set performance correlates with holding-in-mind scores (from the first two trials of an object-retrieval task) (Garon at al., 2014).

Updating.

Violation of expectation paradigms have demonstrated that infants as young as 5 months can maintain and update representations of hidden objects (Koechlin, Dehaene & Mehler, 1997; Wynn, 1992). By 8 months, these updating abilities extend to more complex scenes containing multiple occluded arrays (Huntley-Fenner, Carey & Solimando, 2002, Káldy & Leslie, 2003). Age-based improvements in performance on updating-in-mind measures (such as trials on object-retrieval tasks whereby the previously successful location must be ignored for the new location) follows a similar trajectory to that of holding-in-mind, but with slightly lower scores (Garon et al., 2014).

Indeed, updating-in-mind is generally considered to require both holding-in-mind plus additional inhibitory/attentional control requirements in order to override a previously successful response. For example, performance of 18-30 month olds on a memory-for-location task was related to both increasing age and individual differences in self-control. (Lee, Vaughn & Kopp, 1983), whilst specific updating-mind-scores correlate both with holding-in-mind and simple inhibition scores (Garon et al., 2014).

To date, there is little evidence of stability in updating-in-mind from infancy through to age 3. However, in the one study known to have used a longitudinal design to support investigation of this question the holding-in-mind scores (from the first trials) are conflated with updating-in-mind scores (from subsequent trials). Furthermore, only 50 out of 66 infants successfully completed all 4 trials of this task indicating that the design was not optimal for the age group (Johansson, Marciszko, Brocki et al., 2015).

Amongst infants aged 2 and older, the Spin the Pots task (in which 6 rewards are hidden in view of the infant each in 1 of 8 visually distinct pots, which are covered and rotated between retrieval trials) allows updating-in-mind performance to be calculated using

reverse error scores: infants who retrieve all 6 rewards without searching any empty pots can be assumed to have updated their representation of the hiding places after each trial. Two-year-olds make considerable errors in this task, but reach ceiling by age 4 (Hughes & Ensor, 2007). In one study, performance on Spin the pots showed no individual stability between ages 2 and 3 (Johansson, Marciszko, Brocki et al., 2015) but others have found evidence of stability between Spin the Pots performance at ages 2 and 4, and ages 3 and 4 Hughes and Ensor (2007). One administrative difference between these studies is that in the Johannson, Marciszko, Brocki et al. (2015) adaptation raisins were used (which could be immediately eaten) rather than the stickers of the original version. Changing aspects of tasks so that they become "hotter" (see Box 2) has been found to decrease EF performance amongst pre-schoolers (Carlson et al., 2005).

Shifting.

When a child must change their response behaviour from using one rule (task set) to using another rule, this is known as set shifting (also switching) (Blakey et al., 2016). One of the simplest responses available to the developing infant is the oculomotor response – i.e. the ability to control looking. The ability to exert simple oculomotor response shifting has been observed in some infants as young as 7 months using a gaze-contingent shifting task: In 9 pre-shift trials, 7-month-old infants were consistently presented with a speech or visual cue followed by a visual reward on one side of a screen, and learned to make anticipatory saccades to that side of the screen. In the post-shift phase, the reward was presented on the contralateral side and infants were required to supress anticipatory saccades to the previously rewarded side in order to execute them to the new location. Only a subset of infants were able to do this, all of whom were bilingually-raised infants (Kovacs & Mehler, 2009). At 8 months, both bilinguals and monolinguals were able to inhibit looking at the wrong location, but the bilingual infants showed a tendency to show inhibition earlier (Ibanez-Lillo, Pons,

Costa, & Sebastian-Galles, 2010). Kovacs and Mehler (2009) suggest that despite these infants still being preverbal, bilingually-raised infants have already learned to access the linguistic representations of a current target language whilst avoiding interference from a non-target language. This ability is essentially a form of early set shifting. Once acquired, shifting skills can be applied across contexts, hence the bilingually-raised infants showed enhanced ability in the gaze-contingent shifting task. This bilingual advantage in shifting has been shown across a range of tasks in toddlers and preschool children and appears to be specific to shifting rather than general inhibitory control (i.e. there is no clear bilingual advantage on impulse control tasks) (Bialystok, 2015; Poulin-Dubois, Blaye, Coutya & Bialystok, 2011).

A classic and well-studied measure of response shifting is the A-not-B task (Diamond 1985). In this task, the child watches as the researcher hides a desired object in 1 of 2 identical wells ('A'). After a brief delay, the child is allowed to reach (or, in gaze-based paradigms, look) for the object. The object is then hidden in the same well on subsequent trials until the child reaches to the correct well. After 2 consecutive successful reaches to 'A' the side of hiding is reversed and the procedure repeated. Thus the child must shift their response from one rule (search A) to another rule (search B).

Performance on the A-not-B task follows a linear trajectory with age. By 7½ months infants are able to pass A-not-B tasks, as long as the delay between hiding and retrieval remains under 2 seconds. When the delay increases by a small amount, the resultant errors tend to be perseverative (i.e. consistently searching at location A), but after large delays infants search randomly, showing a preference for neither A nor B (Diamond, 1985). As infants age, the delay between hiding and retrieval necessary to produce an error increases continuously at an average rate of 2 seconds per month, to over 10 seconds by 12 months

(Diamond, 1985). This pattern of improvement continues in the second and third years of life with the percentage correct increasing with age between 15 and 30 months in typical children with a 5 second delay (Diamond, Prevor, Callender & Druin, 1997), and between 23 and 66 months with a 10 second delay (Espy, et al., 1999). However, studies have found low stability of individual differences between 14 and 18 months and 15 and 20 months, raising some concerns about the value of this measure in longitudinal studies of EF (Miller & Marcovitch, 2015; Wiebe, Lukowski, & Bauer, 2010).

The relationship between delay period and error during A-not-B tasks has led many to argue that response shifting errors result from the immaturity of a limited capacity system shared between working memory and inhibitory control: increasing the demand on working memory reduces one's inhibitory control, and vice versa (Engle & Kane 2004; Roberts & Pennington, 1996; Wais & Gazzaley, 2011). To an extent, this argument is supported by Espy et al.'s (1999) finding that performance of 2- to 5-year-olds on A-not-B tasks is driven in part by a factor in common with Delayed Alternation performance (which, as discussed above, we might presume to relate to maintaining), and in part by a factor shared with performance on impulse control tasks (which we might presume to relate to inhibitory control). However, the key to understanding how these two factors interact to affect shifting performance comes from considering the differences in performance that arise from changes in response modality.

Switch costs are task specific (Meiran, 2010). In A-not-B tasks, perseverative errors (returning to the previously rewarded location) reduce significantly when the response modality is changed from reaching to looking (Baillargeon, Devos & Graber, 1989; Hofstadter & Reznick, 1996; Zelazo, Reznick, & Spinazzola, 1998). Similarly, in the gaze shifting task described above, when young adults are given a similar task the bilingual

advantage disappears in eye-tracking versions of the task, but reappears when the response method is changed to a key press (Bialystok, Craik, & Ryan, 2006). Thus, tasks that demand more intensive control efforts – for example because they require an action that is not yet well rehearsed – are more difficult to suppress or shift away from (Meiran, 2010; Thelen, Schoner, Scheier, & Smith, 2001).

Task-specific switch costs have been explained by two influential models: Parallel Distributed Processing (Munakata, 1998) and Dynamic Field Theory (Buss, Wifall, & Hazeltine, 2016; Thelen et al., 2001). Both models prioritise the importance of the memory trace in perseverative responses and hold that inhibitory control in response shifting tasks is itself a behavioural product of working memory; a strong representation of the actions required for the task leads to execution of the action, whereas a weak representation will enable a pre-potent response to win out. These accounts explain why a U-shaped pattern of development is often observed in set shifting performance: perseveration can only occur once the infant has sufficiently developed a skill sufficiently to create a strong memory trace of that performing that skill. In the case of A-not-B tasks, this skill is motor reaching. Before the age of 5 months, reaches are jerky and do not follow a clear trajectory towards the object, thus the motor planning process is too fragile to form the basis of a stable memory trace and consequently, 5-month-olds make few perseverative errors in A-not-B tasks. As the infant develops and his reaches become more fluid and well-planned, the memory trace of the reach to A becomes stronger which, if not modulated, gives rise to a perseverative response on B trials (Clearfield, Diedrich, Smith, & Thelen, 2006). Thus, 13-month-olds perseverate more on an A-not-B variant that involves descending a staircase (a skill which is just developing for most 13-month-olds and which therefore requires considerable attentional effort) compared with a version in which they walk on flat ground (Berger, 2004). As this ability

becomes well-rehearsed and partly automatic, the memory trace one again becomes weaker and levels of perseveration drop.

In some respects then, perseveration in set shifting tasks is actually a sign of developmental achievement on the path to skilled behaviour (Clearfield, et al., 2006) – but this developmental achievement is related to the response modality, rather than to EF itself. The EF 'breakthrough' comes when a strong memory trace can be *selectively* suppressed or activated in line with the demands of the task set (Buss et al., 2016, Thelen & Smith, 1994). This ability is best assessed through conflict tasks, described in the following sub-section.

Meanwhile attentional set shifting tasks, just like response shifting tasks, involve holding in mind and responding according a task set, then shifting to a new task set and inhibiting responses based on the first task set. However, the demands on selective attention placed by the task sets (to selectively attend to one dimension and inhibit attention to another dimension) make the task more challenging. The most well-established of these attentional set shifting tasks is the Dimensional Change Card Sort Test (DCCS) in which children must switch from sorting cards using one set of dimensions (e.g. sort by colour) to another (e.g. sort by shape) (Zelazo, 2006). Three-year-olds tend to be able to sort either by colour or shape (suggesting that they are able to exercise selective attention in the first part of the trial), but fail to adopt the rule change, even though they report back their understanding of it (Zelazo, 2006; Zelazo, Muller, Frye & Marcovitch, 2003).

DCCS-style tasks commonly make 2 demands of children: they must shift their sorting behaviour from using 1 rule to using another rule, and they must resolve the within-stimulus conflict between the previous dimension and the new dimension (Blakey et al., 2016). When this second requirement is removed so that only switching is required, performance on attention shifting tasks steadily improves from 18 months (Garon et al.,

2014). Whilst performance appears initially limited by the demands on the initial task set, improvement on attentional set shifting follows a much slower trajectory than task set performance alone (Garon at al., 2014). However, under the right conditions, the ability to shift their sorting behaviour in the presence of distracting but not conflicting stimuli is demonstrated by around 50% of 3-year-olds (Blakey et al., 2016).

Resolving conflict.

Conflict arises when a stimulus possesses properties that prompt 2 or more alternative responses (e.g. to sort or reach according to the rule in the first versus the second task set) (Blakey et al., 2016). Thus many of the shifting tasks described above can be also characterised as conflict tasks, whereby the correct response on B trials of the A-not-B task or post-shift trials of attentional shifting tasks is in conflict with the memory trace of the appropriate response for the pre-shift trial. When this conflict cannot be resolved, and the first rule is used as the basis for responding, the response is considered to be perseverative.

At age 2½ most toddlers neither switch nor perseverate in the presence of conflict during attention shifting tasks, but seemingly respond at random (Blakey et al., 2016). Following the Parallel Distributed Processing and Dynamic Field Theory arguments, non-perseverative errors might indicate that the representation of the action required for the task (i.e. to select an image based on 1 dimension over another) is not sufficiently strong at age 2 to create a pre-potent response. Indeed, toddlers do not perform above chance on this skill until around 28 months, and continue to improve well past their third birthday (Garon et al., 2014). In order to avoid confounds of skill level and associated differences in the memory trace when considering abilities in resolution of conflict it is thus useful to consider concurrent conflict.

Concurrent conflict can be induced by making two salient characteristics of a stimulus indicate contrasting behavioural responses. In the Spatial Conflict task (Gerardi-Caulton, 2001) the salient characteristics are identity (shape) and position: Children are presented with a simple visual object (e.g. an animal) on one side of a screen and are trained to tap the button which matches the stimuli. The matching button could be either on the side of the stimulus (congruent trial) or the opposite side (incongruent trial). The dominant response is to press the button on the side of the target, irrespective of its identity, or to favour one hand over the other, and 2-year-olds show difficulty in inhibiting this response. During the third year of life the ability to resolve this conflict in order to select the task-appropriate response develops, so that toddlers can perform well above chance by 30 months (Rothbart, Ellis, Rueda & Posner, 2003; Gerardi-Caulton, 2001).

An alternative measure of concurrent conflict can be found in Stroop-like tasks. In one adaptation of the classic Stroop-task (Stroop, 1935), children are shown cards depicting a small fruit nested in a different large fruit (e.g. a small apple in a big banana) and asked to point to each of the small fruits (thereby inhibiting the dominant response to point to the larger image) (Kochanska et al., 2000). Performance on this task improves between the ages of 2 and 3 years, with some evidence of stability of individual differences across this time span, even between different versions of the tasks (Bernier et al., 2012; Carlson, 2005; Hughes & Ensor, 2007; Kochanska et al., 2000). It should be noted however, that despite being designed to minimize verbal demands, these tasks do have a 'verbal threshold': around 9 per cent of 2-year-olds are unable to complete Stroop-like tasks, of whom all have poor verbal skills (Hughes & Ensor, 2005). This pattern may be linked to the important mediating role that language plays in the formulation and maintenance of goal-specific rules (Zelazo, 2015).

Performance on measures of Updating, Shifting and Resolving Conflict may be driven by a common factor relating to cognitive flexibility, which can be dissociated from the behavioural aspects of effortful control. Firstly, levels of random or mixed-responding in the presence of conflict in an attentional set shifting task are associated with concurrent scores on the Spin the Pots task at age 2-4 (Blakey et al., 2016). Secondly, performance on Stroop-like tasks and the Spin the pots task have been found to load onto a common factor at 26 months, distinct from impulse control task performance and with predictive validity to combined scores from Stroop-like and DCCS tasks at age 3 (Bernier et al, 2010; 2012)., Thirdly, the tasks populating each of the two factors in the Bernier et al. (2010, 2012) studies map closely to those in the 'hot EF' versus 'cool EF' factors identified by Mulder et al. (2014) as driving task performance at age 2 (see Box 2). Thus there is some evidence to support the idea that emergent EF can be dissociated into two separable components, as indicated in Figure 1 under the labels Cognitive Flexibility and Impulse Control.

In addition, there is some tentative evidence to suggest that early differences in Impulse Control drive later individual differences in Common EF, whereas Cognitive Flexibility may represent an as yet unfractionated Shifting-Updating factor. As described in the section on Self-Regulation and Reactivity, high performance on impulse control tasks at 14 months predicts high Common EF, but poorer Shifting-specific performance and has no relationship to Updating-specific abilities (Friedman et al., 2011), whilst Johannson, Marciszko, Brocki et al. (2015) found that 12-month-olds' performance on a working memory task was inversely related to 24 month performance on the same impulse control task as used by Friedman and colleagues. Further longitudinal studies spanning the toddler and early school years are required to confirm whether EF is indeed driven by two separable latent variables by age 3, and the long-term stability of individual differences in these variables.

[Box 3] Working memory.

A much studied, but still much debated construct, working memory is depicted in dominant models as a multi-componential system requiring the integration of domain-specific short-term memory and domain-general working memory capacity (also referred to as the Central Executive and the Supervisory Attentional System) (Baddeley & Hitch, 1974; Kane & Engle, 2002; Norman & Shallice, 1986). Working memory capacity relates to the maintenance or activation of information in the presence of interference or response competition; it is thus the 'executive' element of working memory which is employed in processes such as the maintenance, updating and shifting of task set.

Working memory capacity has both an activation mechanism (organising the holding in mind of the task goal and relevant sensory input within short term memory) and an inhibitory mechanism (inhibiting all competing information and processing) (Roberts & Pennington, 1996). The debate over the extent to which capacity limitations arise from processing skills or other resources, such as controlled attention, has been discussed elsewhere (e.g. Gathercole, 1999) and is beyond the scope of this review other than to acknowledge the likely interactive role that control of attention and processing speed both play in working memory, and thus in the maintenance, updating and shifting of task set. It has also been proposed that working memory is equivalent to individual differences in the executive attention network (see Box 1) (Kane & Engle, 2002).

Clinical Implications

Much of the research discussed above considers optimum development of EF, within typically-developing populations. However, EF development is far from optimum in many children, putting them at risk for poorer mental and physical health, as well as reduced academic, social and economic success (Diamond, 2013). Given that early intervention

(before disruption or delay to EF is advanced enough to be measurable with a conventional battery) is most likely to show greatest benefit (Johnson, 2012; Wass, 2015), there is a need for intervention on the basis of risk. There are a number of factors known to increase risk for impaired EF: for example untreated phenylketonuria (Diamond et al., 1997), prenatal cocaine exposure (Espy et al., 1999), prematurity (Anderson & Doyle, 2004; Mulder, et al. 2009) and lower socioeconomic status (Blair, 2016; Clearfield & Niman, 2012; Rhoades, Greenberg, Lanza & Blair, 2011), but the pattern of EF impairment within these groups is varied, and likely impacted by other risk and protective factors which interact during development, meaning that universal prodromal intervention would be unfeasible from a cost-benefit perspective. Thus, more specific risk markers are required.

Documenting the ranges of typical behaviour within domains core to the development of EF is a necessary and urgent first step towards the ability to define behavioural signals of development that are atypical. Whilst early signals do not necessarily have direct clinical utility, they provide a starting point for the development of a diagnostic assessment system and can be used as risk markers when identifying infants most likely to show later EF dysfunction (McFall & Treat, 1999). This review represents a small but significant move towards developing such risk markers by identifying four core domains critical to early EF development (control of attention, self-regulation and reactivity, processing speed and cognitive flexibility) and drawing together examples of measures of individual differences within those domains. Tracking the long-term development of infants displaying such risk markers would likely be useful in improving understanding of the mechanisms involved in developmental disorders in which disruption to EF has been implicated but not consistently found, such as ASD and ADHD (Barkley, 1997; Ozonoff et al., 1991; Rommelse et al., 2011). It may also be useful in developing specific cognitive phenotypes of these heterogeneous disorders (Coghill & Sonuga-Barke, 2012).

The second major clinical implication of this review is in identifying mechanisms for the target and/or delivery of early intervention in infants thought (by virtue of membership in one of the risk groups identified above) or identified (via a behavioural signal of development which fall outside of the typical range in one or more of the four domains) to be at risk of executive dysfunction. A consistent finding of the research reviewed in this paper is that 'positive parenting' approaches (such as relating to responsiveness, scaffolding, sensitivity, attachment and warmth) during infancy impacts on individual differences in self-regulation, control of attention and cognitive flexibility (Bernier et al., 2012; Bernier, et al., 2010; Bibok et al., 2009; Gaertner et al., 2008; Graziano et al., 2011; Kochanska et al., 2000). The current evidence for the efficacy of parent training programmes in improving these skills amongst children already with a diagnosis of ADHD (the most common developmental disorder associated with difficulties in these domains) is muted (Sonuga-Barke et al., 2013). However when programmes are targeted at parents of infants from other groups at-risk for EF problems, effects are more convincing: for example the US Early Head Start program targeting parents and infants from a low-income background showed increases in infant sustained attention and reductions in aggressive behaviour (Love et al., 2005), whilst a smaller-scale pilot study showed provisional indications that parent-training interaction therapy can improve emotion regulation skills amongst 3-year-old children born preterm (Rodriguez, Bagner, & Graziano, 2014) and a positive parenting intervention for parents of infants at high-risk for ASD demonstrated an improvement in infant control of attention (Green et al., 2015). Further research is therefore merited into the benefits of training parents of infants at-risk for executive dysfunction in positive parenting approaches.

Alternatively, since early verbal ability has been linked with performance on set shifting tasks specifically, and EF performance more generally (Barkley, 1997; Carlson et al., 2004; Hughes & Ensor, 2007; Miller & Marcovitch, 2011; Zelazo, 2015) language-focused

interventions may prove beneficial for some groups. Indeed the 'Tools of the Mind' preschooler programme (Bodrova & Leong, 2007) specifically includes a focus on self-regulatory private speech and has been linked to improvement in measures of cognitive flexibility (Blair & Raver, 2014). Currently targeted at 4- to 5-year-olds, it remains to be seen whether Tools of the Mind or similar approaches might show similar effects when adapted for 2- to 3-year-olds.

The evidence base for interventions which might improve EF performance via improvements in processing speed early in life is less clear. Processing speed appears to be largely influenced by genetic differences (Sheppard & Vernon, 2008) although there are some indications that a high-quality diet in infancy (such as from breast milk or DHA-enriched formula milk) may be linked to faster information processing (O'Connor et al., 2001; Willatts et al., 2013). However, improvements in processing speed have also been linked to cognitive training, at least in older adults (Ball, Edwards & Ross, 2007). To date the main focus of cognitive training in children has been on working memory, rather than processing speed specifically, with targeted training showing working memory improvements in children, including those with ADHD (Holmes et al., 2010; Stevens, Gaynor, Bessette & Pearlson, 2015; Thorell, Lindgvist, Nutley, Bohlin & Klingberg, 2009). There is limited evidence of general transfer effects of training to other EF functions in young children (Egeland, Aarlien & Saunes, 2013; Melby-Lervåg & Hulme, 2013; Wass et al., 2015).

A major barrier to establishing which intervention techniques are most effective in improving the early development of EF is the limited baseline and outcome measures commonly used to establish efficacy, both in terms of the number of measures used, their scope (i.e. domain of interest) and the number of time-points evaluated. Given that intervention studies are always restricted by cost and ethics (i.e. load on participants) in the

measures that can be used, a more detailed evidence base is required for the selection of measures most likely to reveal meaningful differences in the early development of EF. Ways of establishing this evidence base are discussed in the next section below.

Methodological Recommendations

As this review has demonstrated, research into domains linked to emergent EF has bloomed over recent years, and with this has come both convergence and divergence. Divergence is most evident in the range of overlapping terminology, and alternative interpretations and applications of similar constructs, used across the literature within and between disciplines. It is hoped that this review will go some way to identifying common ground between constructs and providing a frame of reference for identifying areas of useful collaborative research.

Convergence can be seen in the swell of evidence demonstrating that the foundations of EF are laid well before the age of 3. These foundations are most heavily studied in the domains of control of attention and self-regulation, whilst there are fewer, but nevertheless compelling, studies monitoring the role of processing speed in the early development of EF. In contrast, stability of individual differences in the development of cognitive flexibility has been somewhat overlooked, despite cross-sectional evidence demonstrating the presence of this ability from the first year of life. Thus a recommendation for future research is to confirm the proposed relationship between early differences in maintaining, updating and shifting task set to later cognitive flexibility and broader EF (as illustrated in figure 1).

When considering models of EF development it is tempting to assume a linear pattern in which competency and efficiency increase incrementally over time. However, cognitive development frequently does not follow a linear developmental path, but rather cycles of

jumps and drops (Dawson-Tunik, Commons, Wilson & Fischer, 2005). In each domain of interest, there may be different reasons for shifts in the trajectory of observable differences: in the case of control of attention there is evidence of a period of transition at around 9 months, during which attention systems become more unified; the way in which self-regulation manifests is partially influenced by developmental changes in reactivity and social interactions; improvements in processing speed interact to affect looking times in combination with attentional control; and performance on cognitive flexibility measures are in part linked to the interactive effects of task-specific demands, such as motor-control. It is therefore important when testing any model of EF, figure 1 or otherwise, both to capture data from multiple time-points, so that any temporary drops do not mask an overall developmental trend, but also to carefully control the spread of age ranges within a sample. Unfortunately, this is difficult to achieve with very young children who cannot always be relied upon to be healthy, compliant and alert at the time they have been scheduled for assessment. In longitudinal studies in particular, where an infant visit may need to be rescheduled multiple times to avoid losing them from the study altogether, the variation can drift out from weeks to months. Consequently, it is not uncommon for studies to report the performance of '2-year-olds' on EF measures when actually the mean age is 28-29 months and the range covers the whole of the third year of life (e.g. Hughes & Ensor, 2007; Mulder et al., 2014): this range may mask fluctuations in ability during this critical phase of development.

It should also be remembered that performance on a task at any one point in time does not necessarily fully reflect an infant's EF capability. This is due in part to the task-impurity problem mentioned throughout this review whereby performance may be limited by aspects such as language ability, motor skills and social motivation. For example, many EF tasks require participants to internalise the goal set by the researcher as part of the task set (e.g. to retrieve an object or to sort by a particular dimension, or to point to a particular type of

image) – which may conflict with their own goal (such as to try to nest the cups used for hiding, or to practise building a tower with the blocks that were to be sorted). In these cases, completion of the task is reliant on compliance as much as goal-fulfilment and is thus vulnerable to differences in the level of rapport created between the child and experimenter. Indeed, in their memory for location tasks, Mulder et al. (2014) found around 14% of two-year-olds were unable or unwilling to complete these tasks, whilst of Zelazo et al. (1998)'s initial sample of 54 2-year-olds, 6 (all boys) refused to participate in a multi-location search task, and a further 8 (6 girls) started the task but failed to complete it. Given that compliance and inhibitory control have been found to correlate in younger infants (Kochanska et al., 1998), it is feasible that the results of those who *do* complete the task represent only those with average-to-high compliance and inhibitory control.

Additionally, a child may be willing to complete a task, but have misunderstood the goal or task parameters. In the A-not-B task, for example, infants may interpret the training phase as a communicative task in which the experimenter is trying to teach them to reach to location 'A' – and respond accordingly: when the experimenter is explicitly non-communicative, or when there is no human administrator, accuracy of reaching to 'B' significantly increases amongst 10-month-old infants (Topál, Gergely, Miklósi, Erdőhegyi & Csibra, 2008). Computerised administration, such as using gaze-contingent eye-tracking or touchscreen paradigms, may help to unpick these moderating factors, but this does not negate the need for clear age-appropriate goals in all EF tasks. Indeed, a key recommendation of this review is for more ecologically-valid measures of early EF to be developed which evoke internally-driven goals that are within the range of infants' normal experience (Donaldson, 1978), and which have task constraints (rules) embedded within the materials themselves rather than requiring extensive explanation or modelling (Klahr & Robinson, 1981).

Even when a task is well within an infant's range of competence and experience, there may be wide trial-to-trial variability in performance. This might be caused by temporary fluctuations in motivation or attention linked to recent sleeping and eating patterns, social interactions and the demands of consecutive cognitive tasks (Willoughby et al., 2014), or an artefact of differences in the task itself whereby certain stimuli or settings set up particular expectations for an infant (Goldsmith et al., 1987; Pelphrey et al., 2004). For example, in a problem-solving task requiring toddlers to nest cups together, a child who is currently preoccupied with role-playing drinking from cups may fail to achieve the 'goal' despite being perfectly capable of it. Measuring the EF component in question via a battery of tasks should reduce this problem (Miyake et al., 2000; Willoughby et al., 2010), but will do so best if a variety of task designs are used. This is particularly true in long batteries where motivation is likely to decrease when tasks are similar in kind (e.g. multiple table-top reward retrieval tasks) or where age-appropriate difficulties with sitting still for long periods of time may limit performance. Fortunately, technical developments now make multi-modal batteries using a mixture of table-top, eye-tracking and touchscreen paradigms an achievable option.

Finally, even when carefully designed multi-modal EF batteries are used, care needs to be taken in interpreting the data; rather than interpreting findings as representing the 'best' of an infant's abilities, they should be considered as reflecting performance at a moment in time in the presence of other variables relating to motivation and attention. Researchers should consider the importance of context in heightening the impact of these differences: for example, a child with high reactive inhibition may be more impacted by an unfamiliar laboratory environment than a child with low reactive inhibition. Whilst some differences can be controlled for (for example by testing in the home rather than the laboratory) this may not always be practical, and therefore laboratory measures should ideally be cross-checked against parental report which, in theory, ought to provide an indication of EF-related

behaviour in a broader context. Currently, the only standardised rating schedule attempting to measure the broader construct of EF in children under 3 using parent report is the Behavior Rating Inventory of Executive Function (BRIEF) Preschool version for 2- to 5-year-olds, and this has only been validated with children over 2 and a half (Gioia, Isquith, Retzlaff & Espy, 2002; Isquith, et al., 2004). As yet, no data on the correlations between performance on laboratory 'EF tasks' and BRIEF ratings for typically-developing 2-year-olds is available. This gap in knowledge could hinder development of reliable measures of emergent EF and is therefore a priority for future research.

Conclusions

This review sets out evidence for four domains – control of attention, self-regulation and reactivity, processing speed and cognitive flexibility – which, in interaction with each other and with additional environmental and genetic factors, drive and constrain EF development in the first 3 years of life. A summary of the research presented is provided in Figure 2 to illustrate when measurable abilities within each domain first emerge and when individual differences in these abilities show a predictive relationship to later EF. This pattern of evidence is compatible with an integrative and hierarchical model of EF development whereby early simple skills support the development of, and become integrated into, more complex skills (Garon et al., 2008, 2014).

[Figure 2 to appear here]

Figure 2. Development of skills within domains related to EF: The pale grey bar indicates that there are emerging signs of abilities in this domain within this age band, but limited evidence for stable individual differences; darker grey represents evidence that skills within this domain show a predictive relationship to later EF during this period.

The core foundational domains for EF are posited as control of attention, self-regulation and processing speed, which emerge within the first 6 months of life and have predictive validity to EF by 9 months. The more complex ability of cognitive flexibility begins to emerge in the second half of the first year, building upon those foundational domains in the form of abilities relating to maintaining, updating and shifting task set. However, it is not until the emergence of the ability to resolve conflict, shortly after the second birthday that tasks tapping cognitive flexibility show longitudinal stability. As Figure 1 indicates, the ability to harness cognitive flexibility, alongside the ability to marshal self-regulation in the form of impulse control, can be considered to mark the emergence of EF, towards the end of the third year of life.

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