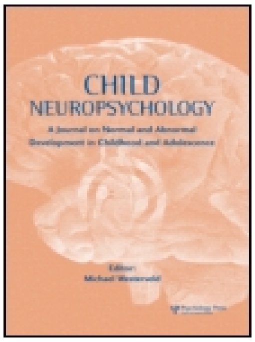

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Assessment and Development of Executive Function (EF) During Childhood

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ABSTRACT

This review paper outlines the issues associated with the assessment of executive function (EF) in children and adolescents, and describes the developmental profile of executive processes across childhood. At the outset, EF is defined, and cognitive and behavioral impairments associated with executive dysfunction (EDF) are described. A developmental model of EF is proposed incorporating four discrete but inter-related executive domains (attentional control, cognitive flexibility, goal setting, and information processing) which operate in an integrative manner to enable ''executive control''. Characteristics that constitute traditional EF measures are discussed, as are the problems associated with test interpretation. The ecological validity of EF tests and neuropsychological assessment procedures are examined, and adjunct methods of measurement are presented to enable a more comprehensive and valid assessment of EF. Based on developmental and normative studies, the maturation of executive domains is mapped. Attentional control appears to emerge in infancy and develop rapidly in early childhood. In contrast, cognitive flexibility, goal setting, and information processing experience a critical period of development between 7 and 9 years of age, and are relatively mature by 12 years of age. A transitional period is thought to occur at the beginning of adolescence, and shortly after ''executive control'' is likely to emerge. In order to confirm our current understanding of EF development and further enhance our understanding of brain-behavior relationships, longitudinal studies incorporating structural and functional neuroimaging are required.

Executive function (EF) is an umbrella term that incorporates a collection of inter-related processes responsible for purposeful, goal-directed behavior (Gioia, Isquith, & Guy, 2001). These executive processes are essential for the synthesis of external stimuli, formation of goals and strategies, preparation for action, and verification that plans and actions have been implemented appropriately (Luria, 1973). Processes associated with EF are numerous, but the principle elements include anticipation, goal selection, planning, initiation of activity, self-regulation, mental flexibility, deployment of attention, and utilization of feedback. Executive processes develop throughout childhood and adolescence, and play an important role in a child's cognitive functioning, behavior, emotional control, and social interaction.

The anterior regions of the brain are thought to mediate executive functioning as deficits in executive skills often follow damage to the prefrontal cortex (e.g., Grattan & Eslinger, 1991; Stuss & Benson, 1986). Supporting this view, functional neuroimaging studies have observed significant activation within the prefrontal cortex in individuals performing EF tests (e.g., Baker

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et al., 1996; Morris, Ahmed, Syed, & Toone, 1993; Rezai et al., 1993). The neural systems underpinning EF are numerous, complex and inter-related with the prefrontal cortex dependent on efferent and afferent connections with virtually all other brain regions including the brain stem, occipital, temporal, and parietal lobes, as well as limbic and subcortical regions (Stuss & Benson, 1984). Damage or loss of function at any level of one of these neural systems may result in cognitive and/or behavioral deficits. As a consequence of this complex neural network, executive dysfunction is not always associated with prefrontal pathology directly, but may be related to network disconnections such as white matter damage or impairment to other brain regions (Alexander & Stuss, 2000; Eslinger & Grattan, 1993). In summary, it may be argued that the integrity of the prefrontal cortex is a necessary, but not a sufficient, condition for intact executive functioning (Della Sala, Gray, Spinnler, & Trivelli, 1998).

Executive Dysfunction (EDF)

Executive dysfunction (EDF) is not a unitary disorder (Gioia et al., 2001). It represents deficits in one or more elements of EF and a variety of presentations is possible. In children, cognitive deficits that may be associated with EDF include poor impulse control, difficulties monitoring or regulating performance, planning and organizational problems, poor reasoning ability, difficulties generating and/or implementing strategies, perseveration and mental inflexibility, poor utilization of feedback, and reduced working memory. In a developmental context, some of these behaviors may not be considered 'deviant,' as in the case of an infant or young child. Therefore, it is critical that developmental expectations of executive processes are well understood.

EF is not exclusive to cognitive processes, but is also implicated in emotional responses and behavioral actions (Gioia, Isquith, Guy, & Kenworthy, 2000). In particular, mood, affect, energy level, initiative, and moral and social behavior can be disrupted in children and adults exhibiting EDF (Anderson, Bechara, Damasio, Tranel, & Damasio, 1999; Barrash, Tranel, & Anderson, 2000; Eslinger & Damasio, 1985; Eslinger, Grattan, Damasio, & Damasio, 1992; Grattan & Eslinger, 1992). Children exhibiting EDF may present as apathetic, unmotivated, and unresponsive, however, others may be impulsive and argumentative. Some children with executive impairment ask embarrassing or socially inappropriate questions and make hurtful statements, suggesting a lack of insight and intuition. They may also struggle to appreciate humor or tell distasteful jokes. Disregarding the consequences of actions and ignoring social rules and conventions may also be an indication of EDF. Inflexibility and rigidity in children is often manifested by a resistance to change activities, an inability to modify previously learned behaviors, and a failure to learn from mistakes. Not surprisingly, many children exhibiting EDF display poor interpersonal skills and experience difficulties maintaining meaningful social relationships.

Executive impairments have been reported in numerous pediatric clinical populations such as attention deficit hyperactivity disorder (Grodzinsky & Diamond, 1992), autism (Bishop, 1993), bacterial meningitis (Taylor, Schatschneider, Petrill, Barry, & Owens, 1996), dyslexia (Levin, 1990), head injury (Garth, Anderson, & Wrennall, 1997), frontal lobe lesions (Eslinger, Biddle, Pennington, & Page, 1999), hydrocephalus (Fletcher et al., 1996), insulin dependent diabetes mellitus (Northam et al., 2001), and phenylketonuria (Welsh, Pennington, Ozonoff, Rouse, & McCabe, 1990). The range of pediatric conditions exhibiting EDF is to be expected given the array of skills and behaviors that are associated with EF. However, the challenge is not identifying EDF, but determining the nature of the impairment and the underlying neural pathology, as this determination will greatly influence intervention and treatment plans.

Conceptualization of EF

Traditionally, EF has been conceptualized as a single construct, being the central executive responsible for multi-modal processing and high-level cognitive skills (Della Sala et al., 1998; Shallice, 1990). However, EF has also been conceptualized as multiple process related systems, that are inter-related, inter-dependent and function together as an integrated supervisory or

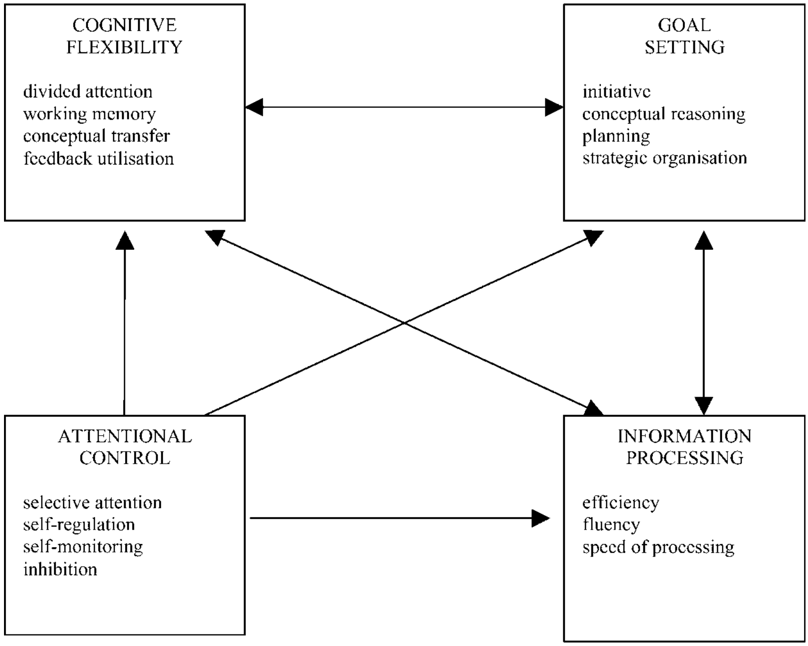

Fig. 1. Proposed model of executive function.

control system (Alexander & Stuss, 2000; Stuss & Alexander, 2000). This latter framework is probably more accurate given that global executive impairment is rare, specific executive processes are thought to be associated with distinct frontal systems, and executive processes demonstrate variable developmental profiles.

In general, developmental models of EF have been derived from factor analytic studies using outcome parameters from EF test batteries (Kelly, 2000; Levin et al., 1991; Welsh, Pennington, & Groisser, 1991). These studies found that variables from EF tests loaded on three to four factors, suggesting that it may be possible to identify specific executive domains and develop an empirically validated model of EF. Interestingly, similar executive factors were reported across studies despite variations in test batteries and small samples across a wide age range. For instance, all three factor analytic solutions describe a "planning" factor (Kelly, 2000; Levin et al., 1991; Welsh et al., 1991), while two solutions refer to impulse control (Levin et al., 1991; Welsh et al., 1991), concept reasoning (Kelly, 2000; Levin et al., 1991) and response speed (Kelly, 2000; Welsh et al., 1991).

Based on factor analytic studies and current clinical neuropsychological knowledge, a model of EF is proposed (see Fig. 1). In line with the views of Alexander and Stuss (2000), this model conceptualizes EF as four distinct domains: (i) attentional control, (ii) information processing, (iii) cognitive flexibility, and (iv) goal setting. These executive domains are considered discrete functions that are likely to be related to specific frontal systems. However, they operate in an integrative manner in order to execute certain tasks, and together they can be conceptualized as an overall control system. Attentional control processes greatly influence the functioning of the other executive domains, while information processing, cognitive flexibility, and goal setting domains are inter-related and inter-dependent. Each domain involves highly integrated cognitive processes, and each receives and processes stimuli from various sources.

The *attentional control* domain includes the capacity to selectively attend to specific stimuli and inhibit prepotent responses, and the ability to focus attention for a prolonged period. Attentional control also involves the regulation and monitoring of actions so that plans are executed in the correct order, errors are identified, and goals are achieved. Individuals with impairments in this domain are likely to be impulsive, lack self-control, fail to complete tasks, commit procedural mistakes which they fail to correct, and respond inappropriately.

In the proposed EF model, *information processing* refers to fluency, efficiency and speed of output. The status of the information processing domain reflects the integrity of neural connections and the functional integration of frontal systems, and can be evaluated by the speed, quantity and quality of output. Information processing deficits include reduced output, delayed responses, hesitancy, and slowed reaction times.

Cognitive flexibility refers to the ability to shift between response sets, learn from mistakes, devise alternative strategies, divide attention, and process multiple sources of information concurrently. In this model, working memory is also an element of the cognitive flexibility domain. Inflexible individuals are generally considered rigid and ritualistic, struggling when activities or procedures are changed and failing to adapt to new demands. Impairment in this domain is often associated with perseverative behavior, with individuals continuing to make the same mistake or break the same rule.

The *goal setting* domain incorporates the ability to develop new initiatives and concepts, as well as the capacity to plan actions in advance and approach tasks in an efficient and strategic manner. Impairments in this domain will result in poor problem solving ability as reflected by inadequate planning, disorganization, difficulties developing efficient strategies, reliance on previously learned strategies, and poor conceptual reasoning.

Assessment of EF

It is argued that executive skills are activated in novel or complex tasks as they require the individual to formulate new plans and strategies and monitor their effectiveness, while simple or routinized tasks are performed instinctively and without the activation of executive processes (Shallice, 1990). Consistent with this premise, Walsh (1978) states that in order to assess EF a test needs to be novel, complex, and involve the integration of information. However, defining a task as routine, overlearned, complex, or novel is not always straightforward as what may be complex or novel for one person may be simple or routine for another (Alexander & Stuss, 2000). Furthermore, some theorists claim that all cognitive tests involve executive functioning to some extent (Alexander & Stuss, 2000; Della Sala et al., 1998; Denckla, 1994).

Test Interpretation

Most current EF tests involve complex, demanding and multi-faceted tasks that tap both executive and non-executive processes, and accordingly, these tests are sensitive to cognitive impairment. However, fractionating the influence of various cognitive processes when interpreting task performance is difficult, and consequently, these tests often lack the capacity to differentiate specific cognitive deficits. An over-reliance on quantitative data when interpreting performance may limit a test's diagnostic utility since personal and situational factors as well as important task behaviors are not taken into account. To overcome this limitation, test performance may be judged using a micro-analytic approach that incorporates quantitative (e.g., success/failure, latency, number of errors, etc.), qualitative (e.g., motivation, energy, attention, distractions, etc.) and cognitive-process (e.g., process, strategies, actions, etc.) methodologies. "Scoring systems" devised to record as much information about task performance as possible are likely to enhance the diagnostic utility of EF tests.

Ecological Validity

Inconsistencies between performance on traditional EF measures and real life behavior are often described (Eslinger & Damasio, 1985; Levine et al., 1998). For example, patients with a history of severe behavioral problems may behave impeccably in clinic, or correctly answer questions about social and moral dilemmas, but lack judgment and self-regulation when faced with similar situations in real-life (Mesulam, 1986). The ecological validity of EF tests comes into question by the very nature of their design, which requires novelty. In addition, neuropsychological assessments are typically administered in well-structured and quiet settings with minimal distractions (Sbordone, 2000), and are unlikely to be representative of home, classroom, or social environments. In the assessment process the examiner provides support and encouragement (Sbordone, 2000), and plans and initiates activities (Anderson, 1998), often becoming the "frontal lobes" of the patient (Stuss & Alexander, 2000). In summary, the one-to-one environment is rarely available in real-life settings, and in some instances, may enhance motivation and performance.

If the ability of neuropsychological test data to predict everyday behaviors is modest (Sbordone & Guilmette, 1999), other sources of information are necessary. Given that EDF affects academic progress and adaptive functioning, assessment of EF should always include family and school interviews as well as qualitative observation (Bigler, 1988; Parker & Crawford, 1992). Behavioral inventories, such as the Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000), are often an useful adjunct to cognitive assessments as they enable behavioral and qualitative information to be collected and interpreted in a standardized format. The BRIEF is a recently developed questionnaire for parents and teachers of school age children, and provides a profile of EF behaviors in home, school, and social environments. The level of agreement between the BRIEF and well-established EF cognitive tasks is at best modest (Anderson, Anderson, Jacobs, Northam, & Mickiewicz, 2002), supporting the view that each form of assessment provides unique information.

Assessment of Pediatric Populations

There is now compelling evidence that executive processes emerge in infancy and develop throughout childhood into early adulthood (Anderson, 1998; Diamond & Taylor, 1996; Espy, 1997; Gerstadt, Hong, & Diamond, 1994). As these skills are vulnerable to early brain damage (Mateer & Williams, 1991) and important for ongoing cognitive development and academic achievement (Dennis, 1989), standardized EF measures are required that are suitable for children and valid for specific developmental stages.

The majority of EF tests used in the assessment of children have been developed and validated in adult populations. In some cases, scaled-down versions of adult measures have been devised (Gnys & Willis, 1991). However, adult-derived tests may be of little interest or relevance to young children, and they often lack adequate normative data necessary to differentiate normal and abnormal performance within a developmental context (Anderson, 1998). Furthermore, the practice of using either adult-derived tests or scaled-down versions in children is questionable, particularly for diagnostic purposes, as adult measures may tap different skills in children and it is yet to be proven that localized dysfunction in adults can be generalized to children (Anderson, 1998; Fletcher & Taylor, 1984).

In the last decade a number of tests have been devised specifically for particular age ranges through childhood (e.g., Anderson, Anderson, Northam, & Taylor, 2000; Delis, Kaplan, & Kramer, 2001; Espy, 1997; Gerstadt et al., 1994; Jacobs, Anderson, & Harvey, 2001; Jacques & Zelazo, in press; Korkman, Kirk, & Kemp, 1998). However, as cognitive functions develop rapidly in children, it is difficult to devise tasks that are suitable across the developmental spectrum. Additional factors need to be addressed when interpreting the performance of children on neuropsychological tests such as the developmental rate of specific skills, and the effects of brain injury on subsequent development. Thus, validating assessment tools within a developmental framework is often more difficult than similar attempts with adult populations.

Development of EF

One of the challenges for understanding EF in children is that these skills develop rapidly through childhood, with the suggestion that progression is not necessarily linear, but may occur in spurts. Further, it appears that components of EF might demonstrate different developmental trajectories, adding to the complexity of the domains. Given that executive processes are dependent on the integrity of frontal lobe systems, it is likely that these skills will demonstrate functional improvements that can be aligned with neurophysiological developments within the prefrontal cortex. Interestingly, the development of the frontal lobes extends into adulthood (Hudspeth & Pribram, 1990; Orzhekhovskaya, 1981; Thatcher, 1991, 1997; Yakovlev & Lecours, 1967). Early claims that executive processes did not emerge functionally until the frontal lobes reached maturity in the second decade of life (Golden, 1981) have now been refuted. For example, neuroimaging studies have demonstrated prefrontal activation in infancy (Bell & Fox, 1992; Chugani, Phelps, & Mazziotta, 1987), while neuropsychological studies have illustrated functional developmental changes on EF tests across childhood (Becker, Isaac, & Hynd, 1987; Levin et al., 1991; Passler, Isaac, & Hynd, 1985; Welsh et al., 1991). Although research indicates that executive processes are present early in life and improve throughout childhood, the developmental profile of these skills is still unclear. Intuitively, one may expect functional improvements in executive skills to be associated with increased maturity of anterior, posterior and subcortical brain regions, as well as the refinement of local connections within the prefrontal cortex and distal connections between the prefrontal cortex and sensory, motor and association regions.

Although most cognitive skills emerge in early childhood, a significant period of development occurs before it is fully functional. Dennis (1989) proposes that this period of skill development can be divided into three sequential stages, emerging (early stage of acquisition and not yet functional), developing (capacity is partially acquired but not fully functional), and established (ability fully mature). Only functional skills are assessable (skills in the developing and established stages), and the impact of brain insults on immature skills may not be realized until later in development when emerging skills become functional. Therefore, an accurate understanding of normal cognitive development is critical for health professionals working with children and adolescents. This knowledge enables earlier identification of developmental deviations, improves diagnostic capabilities, and helps clinicians design age appropriate treatment interventions.

Our current understanding of EF development is based on a small number of developmental and normative studies. Integrating these findings is problematic, however, there is sufficient evidence to suggest that specific executive processes come on-line at different ages and exhibit variable developmental trajectories.

Attentional Control

Infants younger than 9 months of age have difficulty inhibiting previously learned responses, but by 12 months of age most infants can inhibit certain behaviors and shift to a new response set (Diamond, 1985; Diamond & Doar, 1989; Diamond & Goldman-Rakic, 1989). By 3 years of age children inhibit "instinctive" behaviors reasonably well, although they continue to make the occasional perseverative error (Diamond & Taylor, 1996; Espy, 1997). Improvements in speed and accuracy on impulse control tasks can be observed up to 6 years of age (Diamond & Taylor, 1996; Espy, Kaufmann, McDiarmid, & Glisky, 1999). Children aged 9 years and older tend to monitor and regulate their actions well, although an increase in impulsivity occurs for a short period around 11 years of age (Anderson, Anderson, & Lajoie, 1996; Anderson et al., 2000).

Information Processing

In early childhood, increments in response speed and verbal fluency are observed, especially between 3 and 5 years of age (Espy, 1997; Gerstadt, Hong, & Diamond, 1994; Welsh et al., 1991). Processing speed and fluency continues to improve during middle childhood (Anderson et al., 2000; Hale, 1990; Welsh et al., 1991), with significant gains in processing speed observed between 9–10 years and 11–12 years (Kail, 1986). Improvements in efficiency and fluency occur during adolescence (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Kail, 1986; Levin et al., 1991), although increments are likely to be minimal after 15 years of age (Hale, 1990; Kail, 1986).

Cognitive Flexibility

In general, perseverative behavior is common in infancy, declines during early and middle childhood, and is rare in adolescence (Chelune & Baer, 1986; Levin et al., 1991; Welsh et al., 1991). The capacity to switch rapidly between two simple response sets emerges between 3 and 4 years of age, but children in this age range have difficulty switching when rules become more complex (Espy, 1997). Seven-year-olds struggle when switching behavior is contingent on multiple dimensions, however, the ability to cope with these multi-dimensional switching tasks improves greatly between 7 and 9 years of age (Anderson et al., 2000). Switching fluency continues to improve throughout middle childhood and into adolescence (Anderson et al., 2000). The capacity to learn from mistakes and devise alternative strategies emerges in early childhood and develops throughout middle childhood.

Goal Setting

Simple planning skills are exhibited by 4-year-olds but younger children struggle to plan and organize actions in advance (Welsh et al., 1991). Similarly, simple conceptual reasoning is too difficult for 3-year-olds, however, by 4 years of age children are capable of generating new concepts (Jacques & Zelazo, in press). Planning and organizational skills develop rapidly between 7 and 10 years of age (Anderson et al., 1996; Krikorian & Bartok, 1998), and gradually thereafter into adolescence (Krikorian & Bartok, 1998; Welsh et al., 1991). Young children utilize simple strategies which are usually inefficient, haphazard or fragmented, but between 7 and 11 years of age strategic behavior and reasoning abilities become more organized and efficient (Anderson, Anderson, & Garth, 2001; Levin et al., 1991; Waber & Homes, 1985). Despite access to a greater repertoire of strategies, regression from conceptual strategies to piecemeal strategies may occur around 12–13 years of age, suggesting a developmental period in which cautious and conservative strategies are preferred (Anderson et al., 2001). Refinement of strategies and improved decision making continues during adolescence (Anderson et al., 2001; Levin et al., 1991).

Gender Differences

Most research to date indicates that boys and girls develop executive processes at a similar rate during childhood (Becker et al., 1987; Chelune & Baer, 1986; Passler et al., 1985; Welsh et al., 1991). Marginal gender differences have been identified on specific tasks, although these findings have not been consistently replicated in other studies. Areas in which girls have been reported to outperform boys include verbal fluency, information processing and spatial organization (Anderson, 2001; Anderson et al., 2000, 2001; Karapetsas & Vlachos, 1997; Levin et al., 1991). In contrast, boys have performed better than girls on a spatial reasoning/working memory task (Krikorian & Bartok, 1998).

Summary

Research indicates that the executive domains mature at different rates. Integrating the findings from developmental and normative studies, proposed developmental trajectories for executive domains are illustrated in Figure 2. These profiles are hypothetical approximations that require verification in future developmental studies. Processes within the attentional control domain appear to undergo considerable development during infancy and early childhood, and by middle childhood self-control and self-regulation processes are relatively mature. Despite following slightly different developmental trajectories, information processing, cognitive flexibility, and goal setting are all relatively mature by 12 years of age, although many executive processes are not fully "established" until mid-adolescence or early adulthood.

Developmental regressions have been reported between 11 and 13 years of age, particularly in the areas of self-regulation and strategic decision making (Anderson et al., 1996, 2001). This regression may be associated with a transitional period between developmental phases (Kirk, 1985), resulting in conflicts between developing cognitive processes. For example, the implementation of conceptual and "holistic" strategies clashes with the execution of self-regulatory processes, which requires close monitoring of performance and prefers the "de-construction" of tasks. Balancing and prioritizing these competing demands requires "executive control", which may only be possible when each executive domain reaches a certain maturity level.

The protracted development of executive domains is likely to be aligned with neurophysiological changes, particularly synaptogenesis and

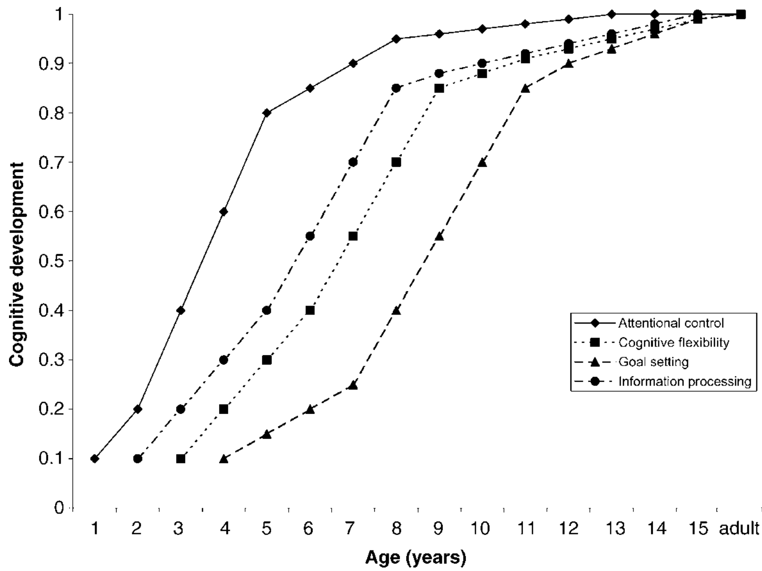

Fig. 2. Projected developmental trajectories of the executive domains.

myelination in the prefrontal cortex. Based on EEG data, five periods of rapid growth in the frontal lobes have been reported which reflect an increase in the number and/or strength of frontal lobe connections (Hudspeth & Pribram, 1990). The first growth spurt in the frontal lobe is from birth to 5 years of age, consistent with significant developmental gains in attentional control processes. The other three executive domains (information processing, cognitive flexibility, and goal setting) exhibit rapid development between 7 and 9 years of age, which interestingly corresponds with the second growth spurt in the frontal lobe. The third growth spurt occurs between 11 and 13 years, the period when all four executive domains approach maturity and ‘‘executive control’’ emerges. In addition, it is clear that myelination of prefrontal connections occurs gradually throughout early childhood, middle childhood, and adolescence (Giedd et al., 1996; Huttenlocher & Dabholkar, 1997; Klinberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999). Progressive myelination is likely to result in more rapid and efficient transmission of nerves impulses, improved information processing, as well as enhanced integration of cognitive processes and improved executive control.

Future Directions

Conceptual models for psychological constructs such as EF provide the framework for devising assessment protocols, the interpretation of test performance and adaptive functioning, and the formulation of treatment and management strategies. In order to confirm or modify existing EF models, large-scale exploratory and confirmatory factor analytic studies are required in the attempt to identify common executive factors and examine their inter-relationships.

Executive functioning involves both cognitive and behavioral elements, however, at times cognition and behavior are discordant. Dissociation between cognitive functioning and behavior/personality attributes may be due in part to the roles of separate prefrontal systems. For example, cognitive aspects of EF appear to be closely linked with dorsolateral regions of the prefrontal cortex, while behavioral manifestations of EDF are more closely aligned with orbital and ventral-medial areas. Research is required to determine the distinctions and overlap between the neuroanatomical correlates of cognitive and behavioral aspects of EF.

Ecologically valid and developmentally appropriate measures are necessary. In the past, EF measures used with children have lacked adequate validation and reliable normative data. Greater selectivity in the tests administer to children is required, ensuring that they are relevant, have undergone adequate standardization, and been validated in appropriate childhood conditions. Given that most cognitive tasks require executive processing to some extent, it may be more relevant to identify performance parameters that are associated with EF rather than labelling specific measures as executive or non-executive. Finally, in order to enhance the diagnostic utility of EF measures, a micro-analytic approach to assessment should be adopted incorporating quantitative, qualitative and cognitive-process techniques.

Our understanding of EF development is predominantly based on cross-sectional studies. Longitudinal designs are considered more valid and reliable for assessing developmental changes, but such studies are rare as they are extremely costly, require many years of follow-up, and are compromised by sample attrition and "learning effects." In the future, longitudinal studies will be required to verify our understanding of EF development. With the assistance of structural and functional neuroimaging, we are now in the position to concurrently track the development of neural systems and cognitive functioning, greatly enhancing our understanding of brain-behavior relationships.

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