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Executive Control Processes: Dimensions, Development and ADHD

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Abstract

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Deficits in higher order cognitive processes such as inhibitory control and working memory (WM), grouped under the term of executive function (EF), have been shown to constitute one important component of the complex neuropsychology of Attention Deficit Hyperactivity Disorder (ADHD). The aim of the present thesis was to examine EF in relation to ADHD, with primary focus on structure (i.e., dimensions) and developmental change. Rooted in the developmental and dimensional perspectives of ADHD, which propose that the disorder represents the extreme of or quantitative delays in traits that are present throughout the general population, four studies (I-IV) based on non-clinical and clinical samples of children at different developmental levels were conducted.

Together, the results from Study I-IV suggest that inhibitory control and WM are important components of EF in typically developing children as well as in relation to ADHD symptoms. Of particular interest are the findings from Study II, III, and IV, showing that inhibitory control and WM seem to be of different importance depending on the child's age. More specifically, the non-clinical and clinical studies suggest that inhibitory control and WM are important in predicting ADHD symptoms, with deficits in inhibitory control primarily being associated with ADHD symptoms for preschool and younger elementary school-aged children, whereas deficits in WM are associated with ADHD symptoms for older elementary school-aged children.

In conclusion, the results of the present thesis are consistent with Barkley's (1997) developmental prediction concerning the relation between EF and ADHD, which suggests that impaired inhibitory control is an early developmental precursor to or a factor that "sets the stage" for deficits in more complex EFs such as WM. The home taking message from the present thesis is that age matters not only in the behavioral, but also in the neuropsychological manifestation of ADHD. To our knowledge, these findings are among the first to show that age is an important factor that should be taken into account in future ADHD research, theory, and treatment.

Keywords: Executive function, development, ADHD, inhibitory control, working memory

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“Completing a PhD thesis must be the ultimate test of one’s executive functions”.

- Karin C. Brocki

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Introduction

Executive function (EF) or executive control is a broad and general construct that refers to the cognitive functions needed for the deliberate control of thought, emotion and action (i.e., goal-directed behavior). There is a long tradition of neuropsychological research attempting to link EF to underlying neurological structures. However, today there is a flurry of empirical activity surrounding executive control processes in many different research fields; with developmental psychology and developmental neuropsychology being two important ones (Zelazo & Mueller, 2002). Motives for the sudden increase in research into EF from a developmental perspective come from evidence suggesting that impaired EF plays a key role in several childhood disorders. Studies that improve our understanding of the typical development of EF may therefore a) provide a clearer picture of the executive control processes thought to be involved in the development of behavioral problems in children and b) facilitate early identification of those children with poor executive and behavioral regulation and who might need intervention. In particular, deficits in EF appear to be one important neuropsychological component involved in the multifactorial etiology of Attention Deficit Hyperactivity Disorder (ADHD; e.g., Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

The present thesis is aimed at exploring the relation between EF and ADHD symptoms from a developmental and dimensional perspective. Particular emphasis is placed on deconstruction of the broad executive construct into its component and sub-component processes and on developmental change as an important factor in the neuropsychological and behavioral manifestation of the ADHD phenomenon. This thesis is based on findings from four studies involving cross-sectional and longitudinal designs, typically developing children, children with diagnosed ADHD, as well as young children identified as having risk for developing ADHD and/or ODD. It is my hope that this thesis will motivate future investigations of a hitherto virtually ignored factor in current ADHD research, that is, the effect of age on the neuropsychological and behavioral manifestation of the ADHD phenomenon.

Before proceeding with accounts of EF in relation to typical development, ADHD, and the dimensional and developmental hypotheses thereof (Levy, Hay, McStephen, Wood, & Waldman, 1997; Barkley, 2003), a general portrayal of the role of executive processes in action control and issues relating to theory and measurement is in order.

What is executive control?

Executive function (EF) or executive control (the two terms will be used interchangeably throughout this thesis) is perhaps one of the most fascinating, yet least understood, aspects of human cognition. Despite the growing interest in and extensive research efforts into the nature of these processes, there is no uniform agreement among researchers as to one exact definition of EF, a shortcoming that could be viewed as reflecting the complexity involved in this cognitive construct. However, most experts agree on the initial generalization that EF refers to higher-order control processes involved in the regulation of thought and action (e.g., Friedman et al., 2006; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). These control processes are particularly invoked in situations that require planning and organized goal-directed thought. For example, Welsh and Pennington (1988, p. 201- 202) describe executive control as “the ability to maintain an appropriate problem-solving set for attainment of a future goal. This set can involve one or more of the following: (a) an intention to inhibit a response or to defer it to a later more appropriate time, (b) a strategic plan of action sequences, and (c) a mental representation of the task, including the relevant stimulus information encoded into memory and the desired future goal-state”. Barkley (1997a) defined executive control as “those types of actions we perform to ourselves and direct at ourselves so as to accomplish self-control, goal directed behavior, and the maximization of future outcomes” (p.57). These definitions illustrate the critical role of EF for successful adaptation and performance in real-life situations, which repeatedly require conscious goal-directed and effortful behavior. They also illustrate the distressing consequences for those with impaired EF.

The unitary view of EF: Theory and measurement issues

One of the problems hindering researchers from agreeing on a common definition of EF has been the tradition of using this term when referring to all functions mediated by the frontal lobes of the brain (Luria, 1966; Shallice, 1988; Shimamura, 1995). Indeed, the association between function and neural structure with regard to EF has been so strong that EFs are spoken of as

synonymous with “frontal functions”. This association has its historical background in neuropsychological studies of patients with frontal lobe damage (and particularly damage to the prefrontal cortex), who show severe problems in control and regulation of their behavior and who function poorly in their everyday lives. Such neuropsychological findings resulted in early theoretical accounts of executive control as a unitary higher order cognitive mechanism or system necessary for regulatory activity (e.g., Luria & Tsvetkova, 1964). The key problem associated with this global conceptualization of EF is that it is too broad and unspecific and therefore commits the philosophical homunculus fallacy (i.e., the erroneous notion that systems in the brain are being run by "little men"). In other words, it does not tell us how goal-directed and deliberate behavior is actually accomplished at a cognitive level. Thus, the question is: What are the specific cognitive processes underlying controlled thought and action?

Other important problems associated with the unitary view of EF are reflected in the fact that commonly used EF tasks are often too global and complex, which results in low construct validity. Low construct validity refers to uncertainty as to the underlying processes tapped by these complex executive tasks, which tend to require a multitude of cognitive processes, executive as well as non-executive (Denckla, 1996). Low test-retest reliability is another methodological problem that many of the complex EF tasks suffer from (Denckla, 1996; Rabbitt, 1997). Instability of test scores over time could perhaps be attributed to the fact that complex EF tasks allow participants to employ various strategies at different test occasions. However, the problem of low test-retest reliability could also be related to the fact that activation of executive processes is thought to be strongest when a task is novel, which in turn would result in reduced taxation of the EF of interest over time. Finally, many of the classical EF tasks have been validated, at least to some extent, on loose decisive factors such as sensitivity to frontal lobe damage (Miyake et al., 2000). As a result of the above-mentioned methodological issues, interpreting and knowing what performance on these tasks really means is problematic.

The so-called task impurity problem (Miyake et al., 2000) can be illustrated by describing one of the most prevalent tasks, which has been considered a classical measure of EF, namely The Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948). This task involves stimulus cards containing objects that vary along three dimensions: color, shape, and number. The cards are presented one by one and the participant is required to sort the cards according to a specific rule defined by the experimenter. Particularly tricky with this task is that the participant is not informed about the sorting rule, but must discover it through trial and error (the experimenter gives feedback after each card played). Further, after a certain number of consecu-

tive correct responses, the experimenter changes the rule without informing the participant. Thus, the participant must not only find the correct sorting rule, but must also be able to inhibit a previously reinforced rule and shift to another one. Patients with frontal lobe damage typically perseverate on this task, applying the rule the same sorting rule over and over again after the switch despite feedback from the experimenter that the response is incorrect. As is apparent from the above description of the WCST, this task involves a wide range of cognitive processes such as “inhibition”, “planning”, “set shifting”, “flexibility”, “problem solving” and “categorization”. Thus, the cognitive requirements for this task and for many other EF tasks as well (e.g., the Tower of Hanoi; TOH, and the Stroop test) are not very well established. Consequently, different clinical groups may perform equally poorly on a specific EF task, like the WSCT, but for different reasons. Thus, our understanding of EF, as studied from various perspectives, would be facilitated if simplified tasks were used that allow comparison of specific and isolated EF components or processes. Taken together, all of the above-mentioned arguments speak for a move away from a unitary conceptualization of EF and in favor of a nonunitary or multicomponential view. That is, the arguments imply that this domain is not a single function, but consists of multiple and separate component functions that together form the ability to regulate thought, emotion and action.

Evidence for the nonunitary view of EF

One line of evidence for the nonunitary nature of EF comes from neuropsychological findings, which challenge the idea of a specific and exclusive link between EF and the prefrontal cortex. Such studies have demonstrated that although there seems to be some commonality between the prefrontal regions supporting different executive demands (Duncan & Owen, 2000), there is also regional specialization within the prefrontal cortex for different executive processes (Shallice et al., 1994). Further, lesion and imaging studies indicate that executive control depends greatly on other structures such as the “basal ganglia (a subcortical group of structures involved in regulating responses), the cerebellum (important in processing timing of events and behaviors), and the corpus callosum (involved in bringing different information together for optimal efficient response”;

 Nigg 2006, p.72).

Baddeley & Hitch (1974; Baddeley & Wilson, 1988) aptly composed five arguments against the classical approach that defines EFs in terms of their frontal location, using Andrés (2003) wordings; “(a) executive processes are not unitary, (b) the frontal lobes represent a large multi-faceted area of the brain, which is unlikely to be unitary in function, (c) executive processes are likely to involve links between different parts of the brain and hence are unlikely to be exclusively associated with frontal location, consequently (d)

patients may conceivably have executive deficits without clear evidence of frontal damage and (e) patients with frontal lesions will not always show executive deficits” (p. 872). Increasing evidence from lesion and neuroimaging studies exists for all of these arguments (reviewed by Andrés, 2003).

Another line of evidence derives from a number of studies using multiple and widely used EF measures to construct “factors” based on factor analysis. Because factor analysis extracts the common variance from multiple measures, task-specific variance and measurement error are largely eliminated, resulting in relatively pure EFs and increased statistical power. Although these studies differ with regard to target population, including normal young adults, brain-damaged adults, typically developing children, and children with developmental disorders (Miyake et al., 2000; Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Levin et al., 1997; Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001), the results tend to reveal a common pattern of separable multiple factors, suggesting that the EF domain is multicomponential.

What these component functions are is being hotly disputed in the current neuropsychological and cognitive literature, but most accounts involve working memory (WM; the ability to hold a goal or relevant information active in mind), inhibitory control or response suppression (the ability to withhold or suppress responses that do not fit with the goal one is trying to achieve), planning, set shifting/task switching and various intentional and motivational functions (e.g., Barkley, 1997a,b; Pennington, 1997; Roberts & Pennington, 1996; Hasher & Zacks, 1988; Fuster, 1997; Goldman-Rakic, 1987). Zelazo and Mueller (2002) acknowledge the functional differentiation of the frontal cortex and divide EF into two main functional categories: “hot” and “cool”. Here “cool” functions are linked to the dorsolateral prefrontal cortex and refer to purely cognitive, abstract and non-arousing aspects of EF. In contrast, “hot” functions are associated with the orbital and medial prefrontal cortex, and refer to affective and arousing aspects of EF. Although most models of EF recognize the above-mentioned component functions as contributors to efficient executive control, albeit to different extents, there is no general agreement as to the nature and definition of these components.

The need for research into the structural and organizational schemes for the components of EF is particularly motivated by evidence suggesting that dysfunctional executive control plays an important role in the manifestation of several developmental disorders, among them ADHD. Indeed, ambiguities concerning the role of EF in ADHD have served as part of the rationale for the ultimate aim of the current thesis, which is to further our understanding of the role of EF in the ADHD phenomenon from a dimensional and

developmental perspective. Clarity as to the neurocognitive impairment associated with ADHD must, at least in part, derive from studies that deepen our knowledge of age-related change in the typical development of EF. However, the study of executive control in children has not been free from methodological obstacles. These issues along with some previous developmental data relevant to the studies included in the current thesis will be described in the following two sections.

Studying EF in children

While investigations of the neuropsychological function of the frontal lobes in adults can be found as early as the end of the 19th century, research examining EF in children has a rather short history, merely spanning the past two decades. One explanation for this neglect of the developmental aspect of EF is the influential, but incorrect assumption that the prefrontal cortex is essentially non-functional in early and middle childhood (Luria, 1973; Golden, 1981). The main reason for this notion has been the understanding that childhood lesions of the prefrontal cortex are silent (i.e., symptomless). However, contemporary investigations with children spanning multiple levels of analysis (behavioral, imaging and neuropsychological studies) have proven this understanding to be wrong. These investigations suggest the existence of rudiments of EF as early as in the first years of life (e.g., Diamond & Goldman-Rakic, 1989; Bell & Fox, 1997; Eslinger, Biddle, & Gratton, 1997), and that significant developmental change occurs between 4 and 7 years (see Zelazo & Mueller, 2002). Although the notion of symptomless lesions in childhood has now been refuted (e.g., Eslinger et al., 1997), case studies show that the direct consequences in children are less obvious than those of a similar lesion in adults (Eslinger et al., 1997). Further, behavioral difficulties may not be noticeable until later in childhood or adolescence, when complex functions typically mature (Goldman & Alexander, 1977; Zelazo & Mueller, 2002).

Although empirical evidence suggests that rudiments of EF emerge very early in life (e.g., delayed response performance in humans; Diamond & Goldman-Rakic, 1989), it is now clear that these cognitive control functions follow an exceptionally protracted course of development. Indeed, several studies suggest that EF develops across a wide range of ages, with performance on many standard EF tests – such as the WCST (Chelune & Bauer, 1986), the Tower of Hanoi (TOH; Welsh, Pennington, & Grossier, 1991) and various WM measures (Luciana & Nelson, 1998; Morra, Moizo, & Scopesi, 1988) – continuing to improve in adolescence and into early adulthood. Such behavioral evidence of executive control is supported by findings suggesting

protracted structural maturation of the frontal cortex. For example, myelination of the prefrontal cortex starts postnatally and has been shown to continue into adulthood (e.g., Yakolev & Lecours, 1967). Further, dendritic and synaptic density in the frontal lobes appear to reach a peak in the first few years of life, with selective pruning of excess connections occurring throughout childhood and adolescence (Huttenlocher, 1990). Development of these structural processes is thought to underlie many of the important functional improvements (e.g., Chugani, 1994; Huttenlocher, 1994).

Most previous studies aimed at assessing EF in children have been based on children of elementary school age. The initial wave of this developmental research (e.g.; Heaton, 1981; Chelune & Baer, 1986; Levin et al., 1991; Welsh et al., 1991) is characterized by methodological and theoretical flaws. These include reliance on adult paradigms, findings or principles (i.e., comparison to normal adult performance and that of brain-damaged adults), using “prototypical” EF tasks with low construct validity, and failure to base the research on theories within developmentally relevant frameworks.

As previously discussed, the issue of low construct validity refers to the possibility that global executive tasks map onto a multitude of cognitive processes, executive as well as non-executive, which makes it difficult to understand the development of individual processes. For example, several of the early developmental EF studies used typical complex and global EF tasks such as WCST and the TOH (Heaton, 1981; Chelune & Baer, 1986; Levin et al., 1991; Welsh et al., 1991). In addition, because there are no agreed-on tasks or set of tasks for assessing each executive domain, it is likely that any observed developmental change based on specific tasks represents different aspects of certain executive domains (Welsh, 2002). This means that previous evidence, based on single tests of developmental change in executive functions runs the risk of being task dependent. The issue of task-dependent measurement was emphasized by Zelazo, Mueller, Frye and Marchowitz (2003, p. 117) when they noted, “certainly it is problematic to compare performance on an easy measure of planning and a difficult measure of rule use and then conclude that planning develops before rule use”. Rushton, Brainerd, and Pressley (1983) underscored aggregation across multiple indicators of a construct as one remedy for the risk of age-related task performance reflecting variance idiosyncratic to a particular task. Welsh (2002) and Wu, Anderson, and Castiello (2002) have also pronounced the advantage of using multiple tests in each executive domain, thereby enabling factor analysis and investigation of developmental trends within the defined domains. Controlling for age in factor analysis further helps to reduce the risk of task intercorrelations being attributed to difficulty level (Carlson & Moses, 2001).

The second issue concerns the fact that developmental research on EF has been guided by principles concerning frontal-lobe functioning in adults, rather than being based on theories within a developmental framework. As Welsh and Pennington (1988) pointed out, by using “adult-like” performance as an indicator for mature executive functioning, one fails to capture the actual process of development in this domain. It may be that scores derived from certain tasks are sensitive to and involve EF in children, but reach an insensitive ceiling in adults. Because EF is age-related, one cannot expect a fixed set of tasks to be sensitive to EF at all age levels. Further, it is important for developmentalists to consider that children’s cognition is not just quantitatively different, but also qualitatively different from that of adults. Consequently, by focusing on the criterion of “adult-like” performance, one may mask the development of EF that is of particular importance in childhood.

Studying EF in young children

Recent years have seen a sudden increase in research exploring executive control in young children (i.e., preschoolers), an upsurge that has been driven by several factors. First, through the study of age-related changes in EF in preschoolers, the earliest forms of precursors of cognitive control can be defined and described. Second, studies based on children of preschool age have important clinical value, as it is now believed that a variety of disorders involving executive dysfunction are manifest as early as in the preschool years. With regard to ADHD, such an assumption is reflected in a change in clinical practice characterized by an increase in children receiving a diagnosis already in the preschool period (Sonuga-Barke & Sergeant, 2005; Zito et al., 2000). This trend has formed a clinical imperative for developmental researchers to identify early neuropsychological risk factors with the aim of better identification of children at risk, and thus early intervention. Further, understanding the roots of the cognitive underpinnings of a disorder will shed light on the complex dynamic interplay between cognitive processes, development, and the social environment, which potentially form the pathways to adverse outcomes later in life (Espy, 2004; Sonuga-Barke & Sergeant, 2005).

The mounting need for investigating early developmental change in executive control has been crucial in forcing developmentalists to recognize the aforementioned methodological issues involved in examining executive control. In other words, the appreciation that “children are not little adults, nor are preschoolers little children” (Espy, 2004, p. 381) is reflected in major methodological advances in research on EF in preschool (the interested

reader is referred to the special issue on executive function in young children published in *Developmental Neuropsychology*, 2004, 26:1). First, there has been a shift away from downward extensions of tests used with adult “frontal-lobe” patients toward more developmentally sensitive measures for young children (e.g., Carlson, 2005). Further, studies have been designed to deconstruct the relative contribution of separate EF component processes in certain problem-solving tasks (Espy, McDiarmid, Cwik, Meade Stalets, Hamby, & Senn, 2004; Beveridge, Jarrold, & Pettit, 2002), and others have modified questionnaires specifically tapping EF in everyday behaviors for use with preschoolers (Isquith, Gioia, & Espy, 2004). However, there is still little agreement as to what measures are appropriate for a certain age range or what measure, or set of measures should be considered as “prototypical” for assessing specific EF components in the preschool as well as school age periods. Thus, the need for careful operationalization and interpretation of executive performance persists, particularly when studying children. Construction of specific rather than global EF tasks will help resolve vexing measurement issues such as task impurity, low test-retest reliability, and thus difficulties interpreting what the results really mean.

The structure and organization of EF

Theoretical and methodological shortcomings of research on EF as studied in both children and adults are, of course, linked to the fact that there continues to be no consensus on the definition of the term EF. According to Borkowski and Burke (1996, p.244), “Perhaps the greatest problem hindering research on EF is a failure to find consensus on a general definition of the construct and then to move from the general definition to a number of operationally specific definitions”. Indeed, structuring of the role and organization of component functions is *sine qua non* for a future universal EF definition. As underlined by Miyake and Shah (1999), it is important to focus research on the relation between core executive functions, their relative independence and whether they even share a common underlying mechanism. Accordingly, with regard to developing a general theory of EF, the past decade has seen important advancements in the form of a flurry of empirical activities focused on deconstructing the umbrella term into its component processes and their interrelations, both in the adult and developmental research area (e.g., Miyake et al., 2000; Friedman et al., 2006; Kipp, 2005; Miyake & Shah, 1999; Kane & Engle, 2002; Hasher & Zacks, 1988; Beveridge et al., 2002; Roncadin, Pascual-Leone, Rich, & Dennis, 2007).

Recent research has resulted in a number of theoretical models in which the broad executive construct has been reconceptualized in terms of a smaller set of core component functions, which may be of primary importance for, or serve as common underpinnings of, executive control (Baddeley & Hitch, 1994; Barkley, 1997a, b; Roberts & Pennington, 1996; Miyake et al., 2000; Kane & Engle, 2002; Fuster, 1997). In other words, attempts have been made to build hierarchical models of the organization of EF, specifying primary and subsidiary functions. Indeed, one of the key controversies in the research literature on EF revolves around what components should be considered as superordinate or primary in relation to other subsidiary components, which depend on or derive from these superordinate components. Although such efforts remain to be empirically verified, they have resulted in several theoretical accounts in which prominent roles are particularly given to inhibitory control and WM (Baddeley & Hitch, 1994; Barkley, 1997a, b; Roberts & Pennington, 1996; Miyake et al., 2000; Kane & Engle, 2002; Hasher & Zacks, 1988). In fact, Miyake et al. (2000) suggested inhibitory control and WM as possible candidate components for common underpinnings of EF in general. However, views on the extent to which inhibitory control and WM are separate, interdependent functions, or which is superordinate the other, vary with number of theoretical accounts and thus this issue deserves further investigation. An attempt will not be made here to cover all of the theories referred to above. Instead, detailed descriptions will be provided of the two models that have served as the theoretical basis for all of the studies included in the current thesis. Both models emphasize inhibitory control and WM as two core EF domains.

Two models of the component functions of executive control

Two models that have had particular influence on our understanding of successful executive functioning, as revolving around inhibitory control and WM in normal adult functioning, typical development, and atypical development, are the hybrid model of executive functioning proposed by Barkley (1997a, b) and the interactive framework proposed by Roberts and Pennington (1996).

Barkley's hybrid model of executive functioning

Barkley's Hybrid Model of EF is founded on prior theories of the neuropsychological functions of the brain's prefrontal cortex (e.g., Bronowski, 1977, 1977; Fuster, 1989) and is probably one of the most sophisticated models available on the organization of component functions, which, according to Barkley, is synonymous with executive control. This model is also one of the few that has implications for the typical development of EF and regulatory

control. In this hierarchical model, Barkley (1997a,b) puts inhibitory control at the top, which means that inhibitory control is the primary executive component upon which four other executive components are dependent. Inhibitory control is divided into three different types: inhibition of prepotent response (i.e., responses that have been reinforced in the past), stopping of ongoing responses (i.e., permitting a delay in the decision to respond) and interference control (i.e., resistance to distracters). Together, these inhibitory functions “set the occasion” (Barkley, 1997b, p. 68) for WM (verbal and nonverbal), self-regulation of affect, motivation and arousal, and reconstitution (analysis and synthesis of information).

WM particularly refers to the capacity to maintain information in mind and use that information to guide immediate behavior in the absence of informative external cues (Goldman-Rakic, 1995). Although Barkley fractionated WM into two primary components—verbal WM (internalization of speech) and nonverbal WM—he also pointed out that there may be as many forms of WM as there are forms of human sensorimotor behavior that can be self-regulatory and covert (Barkley, 1997a, b). In the self-regulation of affect, motivation and arousal component, a self-regulatory part of the executive system is emphasized in that emotions are presumed to be regulated by self-directed, executive actions. This component also includes the self-generation of drive or motivational and arousal states, necessary for the maintenance and completion of goal-directed behavior. Thus, the ability to self-regulate and bring about emotional states as a support for goal-directed behavior also incorporates the intelligence to adjust and induce motivation and arousal in maintenance of behavior. The reconstitution component of Barkley’s model represents two interrelated activities—analysis and synthesis—and can be explained as the ability to separate units of behavioral sequences (analysis) and recombine them in creative ways into new sequences of behavior (verbal or nonverbal). To sum up, the four executive functions are thought to free behavior from being controlled by the immediate environment, to provide a sense of time, and to provide for behavior that is intentional and purposive.

Concerning development of EF, Barkley (1997a) speculates that there is a progressive development of inhibitory functioning in parallel with the structural maturation of the prefrontal regions of the brain, and that the development of general EF is dependent on an increase in inhibitory resources. Consequently, younger normal children should be, according to Barkley, less efficient in inhibitory control, and in turn, in all the four executive functions depending on it, than are older normal children.

Roberts and Pennington's interactive framework of inhibitory control and WM

Barkley's theoretical model bears similarities to the formulation by Roberts and Pennington (1996), which proposes that the interaction between WM and inhibitory function may be sufficient to characterize cognitive and behavioral development within the executive domain. This model follows the assumption that WM and inhibitory control share a common mechanism and thus make use of the same limited-capacity pool of resources. Thus, a task that involves strong incorrect prepotencies, either acquired from reinforcement over previous trials or from preexisting stimulus-response associations, requires higher and more consistent WM activation in order to avoid falling prey to the prepotency and instead execute the correct response. In other words, successful performance on EF tasks boils down to WM and inhibitory function. Like Barkley, these authors argue that there is no qualitative distinction between the processes underlying normal and abnormal executive functioning. Rather, these processes are thought to lie on a continuum, such that success or failure of executive control depends on the interactions between inhibition and WM. According to this formulation, the development of executive functioning should be described in terms of the development of the two fundamental cognitive processes: inhibitory control and WM.

Executive dysfunction in ADHD

Groups of individuals diagnosed with ADHD are heterogeneous with regard to a number of factors. For example, variations in degree of symptoms, age of onset, the extent to which other disorders co-occur and degree of functioning with regard to motor and mental skills have been readily observed (e.g., Nigg, 2006; Barkley, 2006). However, one of the most prominent neuropsychological findings associated with ADHD is weakness in several key EF domains (Willcutt et al., 2005). Although relatively robust, the empirical link between EF and ADHD is also complex and controversial. Therefore, the following sections will deal with issues necessary to illustrate a fair picture of the role of EF in the manifestation of the ADHD phenomenon.

Today there is general agreement that the ADHD syndrome most likely can be caused by multiple etiological factors (e.g., Castellanos & Tannock, 2002; Banaschewski et al., 2005; see Barkley, 2006, for a review).

Box. 1 Attention Deficit Hyperactivity Disorder (ADHD)

Symptoms and Prevalence

ADHD is an externalizing disorder characterized by two behavioral symptom domains: inattention and hyperactivity/impulsivity (DSM-IV-TR; American Psychiatric Association, 2000). According to APA (2000), patterns of inattention and hyperactivity/impulsivity must occur more frequently and be more severe than is typically observed in individuals at a comparable level of development. DSM –IV-TR identifies three subtypes of ADHD: combined type (ADHD-C), predominantly inattentive type (ADHD-PI), and predominantly hyperactive-impulsive type (ADHD-PHI). The official prevalence estimate for all types of ADHD is 3-7%, with a boy:girl ratio ranging from 2:1 to 9:1 (APA, 2000; Tannock, 1998). Between 40 and 90% of children with ADHD qualify for a comorbid diagnosis of Conduct Disorder (CD) and Oppositional Defiant Disorder (ODD; Tannock, 1998).

Etiology

Currently, there is general agreement that the etiology underlying ADHD is heterogeneous (Barkley, 2003). Etiological factors include variations in genetic and environmental factors and, importantly, interactions between genes, and between genes and the environment, leading to variance in the phenotypic manifestation of the disorder (Castellanos & Tannock, 2002). Evidence points to neurological and genetic factors as major contributors to ADHD. Neurological deviations involve a 10-12% smaller size in brain areas such as the anterior right frontal regions, in the basal ganglia, and in the corpus callosum (see Nigg, 2006, for a review). Further, imaging studies suggest that these regions are not only structurally different in children with ADHD, but also show reduced metabolite activity compared to controls (Rubia et al., 1999; Durston et al., 2003). Although not conclusive, evidence suggests neurochemical abnormalities in ADHD, with possible deficiency in dopamine and norepinephrine (Barkley, 2006). Finally, the best-established etiological factor for ADHD is supported by compelling evidence showing that this disorder is highly heritable, with estimates exceeding .70 (reviewed in Castellanos & Tannock, 2002). Although major risk genes remain to be identified, genetic studies have provided strong evidence that it is genes that primarily influence the functioning of the dopamine system that is involved in ADHD (reviewed in Stevenson et al., 2005).

Treatment

To date, stimulant medication (i.e., methylphenidate and amphetamines) is considered to be the most effective treatment for the behavioral symptoms of ADHD (Connor, 2006). Such evidence corroborates a neurochemical abnormality in ADHD. Other treatments involve psychosocial interventions such as parent training and social skills training. It has been suggested that optimal treatment for ADHD is likely to involve a combination of medical and psychosocial approaches (e.g., Phelps, Brown, & Power, 2002).

Using Nigg’s words, “ADHD may have etiological “types”, although these are not yet recognized or agreed upon in the field” (2006, p.176). Studying the neuropsychological profiles of children with ADHD has constituted a popular approach for investigating mediating genetic influences on the phenotype (see Figure 1). In other words, researchers have been searching for a common specific neuropsychological endophenotype (“heritable quantitative traits that index an individual’s liability to develop or manifest a given disease”; Castellanos & Tannock, 2002, p. 617), as a way of understanding why this disorder develops (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005).

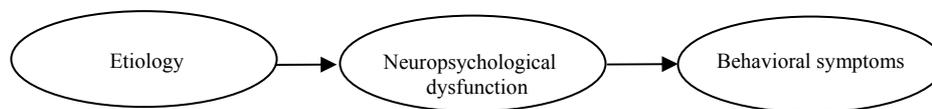


Figure 1. Nigg’s (2006) simplified model of etiology. Reproduced by permission from Guilford Press.

During the past decade, several theoretical formulations have been presented to account for the complex neuropsychological impairments associated with ADHD. In line with the initial assumption of causal homogeneity, these theories have tended to focus on the role of single common core deficits in psychological constructs such as: dysfunctional EF due to difficulties with inhibitory control (Barkley, 1997a,b), regulation of arousal/activation (Sergeant, Oosterlan, & van der Meere, 1999), delay aversion (aversion to delay and consequently difficulties in waiting for motivationally prominent outcomes; Sonuga-Barke, Taylor, Sembi, & Smith, 1992) and in reinforcement mechanisms (Sagvolden, Aase, Zeiner, & Berger, 1998; Sagvolden, Johansen, Aase, Zeiner, & Russel, 2005). However, researchers now advocate a move away from causal models of ADHD, focusing on a single core neuropsychological deficit that would hypothetically apply to every child with ADHD. Instead, in accordance with the contemporary view of etiological heterogeneity, it has been suggested that the different neuropsychological deficits are each needed to best capture the problems of subgroups of children with ADHD, corresponding to neuropsychologically distinct subtypes or endophenotypes of ADHD (Sonuga-Barke, 2005; Nigg, 2006; Castellanos & Tannock, 2002).

The distinct dysfunctional aspects emphasized in each of the theoretical models described earlier most likely represent parts of the neuropsychology of the ADHD phenomenon. However, research is still required to assess the causal status of each candidate pathway, respectively. In other words, more

work needs to be done to examine whether several distinct neuropsychological dysfunctions all can result in typical ADHD behavior. This thesis emphasizes EF in relation to ADHD, underscoring unresolved issues relating to development, and isolation of component executive processes.

EF in ADHD - what is known and what is not?

Indeed, impaired executive functioning is now recognized as one of the primary components of the complex neuropsychology of ADHD (e.g., Willcutt et al., 2005; Castellanos et al., 2006). Substantial evidence exists for structural, functional and neurochemical brain differences in ADHD, in regions that are considered key for EF (see Box 1). Data showing well-replicated group deficits on relevant EF tests are also available (Barkley, Grodzinsky, & Du Paul, 1992; Nigg, 2001; Pennington & Ozonoff, 1996; Schachar, Mota, Logan, Tannock, & Klim, 2000). Associations between ADHD and deficits in prepotent response inhibition constitute the most robust findings (Nigg, 2001; Willcutt et al., 2003).

Importantly, however, mean effect sizes for EF measures seem to be only moderate (e.g., Willcutt et al., 2003; Nigg, 2006), suggesting that deficits in EF should not be considered a causal factor in all cases of the disorder. As discussed previously, it is likely that only a subset of children with ADHD may account for the group effects, whereas others may have dysfunction in other neuropsychological domains such as regulation of arousal/activation (Sergeant et al., 1999) or in reinforcement-response abnormalities (Sagvolden et al., 1998; Sagvolden et al., 2005). The moderate effect sizes observed in EF as well as discrepancies with regard to EF deficits in ADHD may also be related to the shortage of well-established construct validity for EF tasks. As discussed earlier, this task impurity problem makes it difficult to understand impaired performance derived from typical EF tasks, as the separate component processes involved are very hard to identify. Further, as there is no consensus among researchers on a task or set of tasks to assess specific component functions, the tasks chosen in specific studies investigating EF deficits in ADHD may tap variations of a given EF domain (Welsh, 2002). Thus, use of simplified tasks that allow comparison of specific rather than global measurements will help us interpret moderate effect sizes on EF tasks and inconsistencies in results on EF performance in ADHD studies. The development of such measures will indeed be facilitated by models that give structure to possible EF components and the relations between them.

Barkley's hybrid model of EF in relation to ADHD

Perhaps the most influential and comprehensive account of the neuropsychological deficits underlying ADHD is Barkley's (1997a, b) developmental

model of the hierarchical organization of EF, described earlier. Barkley (1997a, b) holds that the primary neuropsychological deficit in ADHD is in inhibitory control (i.e., prepotent inhibition, interruption of an on-going response and interference control). This primary deficit in inhibition in turn impairs the four other executive components necessary for self-regulation of behavior, cognition and emotions, those being WM, internalization of speech/verbal WM and reconstitution (see p. 18 of this thesis for a fuller account of Barkley's model).

Barkley's model has been criticized for being one of the theories that attempts to explain a common core neuropsychological deficit that should be necessary and sufficient to cause all cases of ADHD, at least with regard to the combined subtype (e.g., Castellanos & Tannock, 2002; Sonuga-Barke, 2005). As mentioned earlier, this is most likely not the case, as can be reflected in moderate effect sizes for EF tasks and discrepancies in EF performance across studies. Nevertheless, Barkley's model, until proven otherwise, has explanatory power for understanding the neuropsychology underpinning the ADHD subgroup characterized by EF deficits. In addition, Barkley's theory also has important theoretical advantages in relation to how ADHD should be conceptualized with respect to development and whether ADHD is best viewed as a categorical or a dimensional disorder. These issues have important implications for future ADHD research and theory and therefore deserve further attention.

ADHD - A developmental and dimensional disorder

Barkley (1997a; 2003) advocates a move away from current diagnostic criteria of ADHD (i.e., DSM IV-TR-2000) that characterize ADHD as a categorical and static disorder, with symptoms remaining essentially the same regardless of age. Instead, Barkley along with other researchers such as Edmund Sonuga-Barke, propose that ADHD is a dimensional and developmental disorder (Barkley, 1997a; 2003; Sonuga-Barke, Dalen, Daley, & Remington, 2002; Sonuga-Barke, Dalen, & Remington, 2003). To be more specific, viewing ADHD as a dimensional disorder means that clinical features of ADHD are taken to represent the extreme end of normal traits, rather than as a distinct category. Further, viewing ADHD as a developmental disorder means understanding it as a delay in the rate at which a normal trait develops. Therefore, quantitative rather than qualitative deviations in EF should be predicted in children with ADHD as compared to normal controls. Barkley's model is, to our knowledge, the only one that allows for specific developmental predictions with regard to executive control in relation to ADHD. Interpreting Barkley's model from a developmental perspective, ADHD is grounded in early manifested deficits in inhibitory control, which

in turn will give rise to subsequent impairments in later developing and more complex EFs, such as WM and planning.

The most critical support for the continuum model of ADHD is perhaps the genetic findings of Levy et al. (1997), which suggest that ADHD is inherited as a trait with variable expression throughout the entire population. These genetic findings based on school-aged children have been complemented by behavioral findings showing a linear relation between inhibitory function and ADHD symptom severity in the preschool period (e.g., Sonuga-Barke et al., 2002; Sonuga-Barke et al., 2003; Berlin & Bohlin, 2002). It follows from the dimensional view that performance on tasks that are sensitive to neuropsychological functions reflecting potential ADHD endophenotypes should correlate with continuous ADHD symptom scores in the general population (e.g., Kuntsi, Andreou, Ma, Börger, & van der Meere, 2005; Sonuga-Barke et al., 2002) and that such studies should therefore provide information about potential neuropsychological endophenotypes. There is a scarcity of studies on executive processes in relation to ADHD from a dimensional perspective. Instead, previous research has mainly been based on categorical approaches to ADHD. This means that most extant studies within this field have investigated categorical group differences between ADHD children and normal controls. However, the dimensional perspective implies that an important complement to this research field would be studies of population-based samples using dimensional rather than categorical analyses (e.g., see Barkley, 1997a; 2003; Nigg, 2001). Such population-based samples allow researchers to explore the relation between executive functioning and ADHD symptoms using the full range of severity symptoms.

In line with Barkley's developmental view on ADHD, the classical notion of ADHD as a static disorder is now giving way to a new perspective that highlights ADHD as a developmentally relative deficit, in which the expression of ADHD symptoms undergoes change with age (i.e., the developmental hypothesis; Barkley, 2003). Indeed, symptoms of hyperactivity have predominantly been observed in younger children and shown to decrease with age, whereas symptoms of inattention have been found to be more stable across childhood (Hart, Lahey, Loeber, Applegate, & Frick, 1995). Research to date, however, has not effectively examined the effect of age on the relation between neuropsychological processes shown to be impaired in ADHD and typical behavioral symptoms associated with the disorder. Such data should constitute an important step toward a more well-founded understanding of the ADHD phenomenon as a developmentally relative deficit. Information on developmental effects in the relation between neuropsychological functions and typical ADHD behaviors should also be of direct relevance in the search for potential endophenotypes (Castellanos & Tannock, 2002), which may well vary with age.

EF as a potential developmental pathway in ADHD

Impaired executive processes and particularly inhibitory control are now recognized as one of the critical neuropsychological abnormalities associated with at least one subgroup of children with ADHD (e.g., Willcutt et al., 2005; Castellanos et al., 2006). However, previous studies have mainly focused on school-aged children and have not included longitudinal data. Studying neuropsychological deficits in preschool-age children is important considering the theoretical importance of this period in neuropsychological accounts of ADHD. For example, according to Barkley's (1997a, b) model, one would primarily predict inhibitory dysfunction to be associated with ADHD during the preschool years. Inhibitory deficits are therefore seen as the developmental precursor to more general and later developing EF problems. Further, the need for longitudinal studies has been made clear by the up-and-coming perspective on ADHD as possibly developing along distinct and multiple neuropsychological pathways, of which impairments in EF most likely constitute one. In order to determine such pathways, longitudinal studies tracking the unfolding of key domains such as EF, reward response or regulation of arousal/activation, using age-appropriate tasks, are necessary (e.g., Banaschewski et al., 2005; Nigg, 2006; Sonuga-Barke & Sergeant, 2005). Obtaining a better understanding of the roots of executive control would have potential implications for early detection of and intervention in this disorder.

Further, it has been stressed that longitudinal studies are needed so that pathways between potential risk factors and later manifestation of the disorder can be distinguished from transient behavioral disturbances. In light of this discussion, a number of important research questions have been brought to the fore. First, are the same neuropsychological mechanisms (e.g., executive processes) known to be associated with ADHD in the school years also associated with its preschool equivalent? Second, are these mechanisms specific to behavioral problems primarily associated with ADHD in the preschool years? Third, can impairments in executive components in the preschool years predict symptoms of ADHD over time?

Comorbidity and ADHD

More than half of the children with ADHD qualify for a comorbid diagnosis (Biederman et al., 1992). ODD and CD are the most common comorbid disorders (Loeber et al., 2000), followed by anxiety and depression, and specific learning disability (Tannock, 1998). Related to disorders co-occurring with ADHD is the important issue of specificity, that is, whether a particular executive or other deficit attributed to ADHD can be shown to be related to other psychiatric disorders as well. For example, a deficit in WM may be present in both ADHD and CD, but may be causal in only one of them. Alternatively, such a deficit may be causal in both of them (Nigg, 2006).

Regarding the specificity of EF in relation to ADHD, CD and ODD, results have been conflicting (e.g., Sergeant, Geurtz, & Oosterlaan, 2002 versus Oosterlaan, Scheres, & Sergeant, 2005). Recently, however, a number of studies have been consistent in showing that impaired executive control in ADHD cannot be explained by comorbid conditions. That is, when studies have statistically controlled for symptoms of ODD, CD or reading disorders (and IQ), impaired EF remains in children with ADHD (Nigg, Carte, Hinshaw, & Treuting, 1998; Nigg, 1999; Oosterlaan et al., 2005; Schachar et al., 2000).

There is a scarcity of empirical studies investigating the relation between EF and ODD/CD in preschool children, but the few clinical and non-clinical studies available in the literature suggest that impaired executive control, and particularly inhibitory control, should primarily be considered an associate of preschool ADHD rather than of ODD (e.g., Berlin & Bohlin, 2002; Sonuga-Barke et al., 2002, 2003; Thorell & Wåhlstedt, 2006). However, to our knowledge, very few longitudinal studies have, as yet investigated the extent to which preschool-age executive impairments are specific to subsequent ADHD, ODD and/or CD by controlling for comorbidity in the analyses. Such studies should be of significance, particularly when searching for early neuropsychological risk factors specific to ADHD.

Aims of the current thesis

I have conducted four studies with the ultimate aim of furthering our understanding of EF in relation to ADHD, taking a developmental and dimensional perspective on this disorder. My studies have involved cross-sectional and longitudinal designs, typically developing children, children with diagnosed ADHD, as well as young children identified as being at risk for developing ADHD and/or ODD, spanning a wide range of ages. The specific aims divided into the central themes of this thesis – Dimensions, Development and ADHD – are stated below:

EF Dimensions: Normal children and in relation to ADHD

- To investigate the dimensional structure of the broad executive construct in normal children through factor analysis. Knowledge of such structural organization of executive control in typical development should be important for analyzing and understanding EF deficits in children with ADHD (Study I).
- To study different types of inhibitory control and WM processes in relation to ADHD symptoms in a non-clinical sample (Study II), in a sample including children at risk for developing ADHD and/or ODD (Study III), as well as in a clinical ADHD sample (Study IV).
- To examine whether deficits in WM processes are independent of deficits in inhibitory control in children with diagnosed ADHD (Study IV).

Development of EF: Normal children and in relation to ADHD

- To investigate typical development on salient executive dimensions obtained through factor analysis. Results from such analysis should represent maturational effects within the defined EF domains, rather than age-related variance idiosyncratic to particular tasks (Study I).

- To study developmental change in the relation between EF and ADHD symptoms in a non-clinical sample. This is an important issue with regard to the developmental and dimensional perspectives of ADHD, which implies that one should not assume that the neuropsychological and behavioral manifestation of ADHD is the same regardless of maturational stage (Study II).
- To examine the pattern of associations between inhibitory control and WM and clinical levels of ADHD symptoms in children at different developmental stages: preschool age (Study III) and elementary school age (Study IV). In Study III we also wished to examine relations between EF and 2-year longitudinal ADHD symptoms. Such data should contribute in the search for early neuropsychological risk factors for later developing ADHD. In addition, by including children at risk for ADHD and/or ODD in Study III, we had the opportunity to study how specific EF deficits are to early ADHD symptoms.

Empirical Studies

Participants and procedures

Cross-sectional Studies (I and II)

Study I and II were based on a normal sample of 92 participants (51% boys). The participating children were between 6 and 13 years of age and were recruited through convenience sampling from preschools and elementary schools located in different parts of Sweden. The recruitment of participants was initiated by receiving verbal consent from head principals and teachers at the specific schools. Subsequently, parents were contacted by mail and asked to return a written consent form. In addition, verbal consent from the participating children was obtained prior to the assessment session.

To facilitate the study of developmental change in separate executive functions in a thorough manner in Study I, the sample was divided according to age into four age groups (6 – 7.5 years, 7.6 – 9.5 years, 9.6 – 11.5 years, and 11.6 – 13.1 years). To increase the statistical power of the analysis of developmental change in the relation between EF and behavioral problems associated with ADHD in Study II, the sample was divided into two larger age groups (6 – 9.7 years and 9.8 – 13 years). All 92 children were tested individually in a quiet room at their respective school, with the executive tasks being administered in a fixed standardized order. The children were compensated with a gift for their time and effort worth approximately 50 SEK.

Longitudinal Study (III)

In Study III, a total of 72 children (83% boys) participated. In order to obtain a sample of children scoring across the full range of ADHD symptom severity, 1/3 of the children were recruited from local Child Health Care Centers; these children had previously been identified by child psychologists as being at high risk for primarily developing diagnosable ADHD and/or ODD. The

sample was supplemented by a group of normal children chosen to be proportional to the risk sample in terms of the boy:girl ratio as well as age. These children were randomly selected and recruited through the local birth register of Uppsala County, Sweden. No children in the study were receiving psychostimulant medication for ADHD at the time.

At Time 1 (Age: $M = 5$ years, 5 months; $SD = .69$), the children were tested individually at the Department of Psychology, Uppsala University. The 7 tasks analyzed in the current paper were part of a larger battery designed to tap various executive functions. In an attempt to avoid possible fatigue effects, the tasks were administered during two sessions over a period of 1 to 2 weeks. The tasks within each session were administered in a randomized order. Each session lasted approximately one hour with a break half way through. At the end of each session, the children received a gift worth approximately \$7. At Time 1, questionnaire data from the children's parents and teachers were collected for 72 and 68 of the children, respectively. Reasons for attrition were that parents did not give consent to contact the teacher ($n = 1$) and some teachers were not willing to fill out the questionnaire ($n = 3$). At Time 2 (Time 2 took place approximately 2 years following Time 1 measurements; Longitudinal gap $M = 2$ years, 2 months; $SD = 0.28$; Age: $M = 7$ years, 6 months; $SD = .47$), questionnaire data from the children's parents and teachers were collected for 66 and 65 children, respectively. Reasons for attrition were that the family had moved out of the area ($n = 2$) or that the family no longer wished to participate ($n = 4$). Further, parents did not give consent to contact the teacher ($n = 1$).

Clinical Study (IV)

Two groups of 7- to 12-year-old boys ($M = 10.11$ years, $SD = 1.63$) participated in this study. The first group included 31 boys diagnosed with ADHD, Combined Type ($M = 9.97$ years, $SD = 1.72$) and the second group included 34 boys without ADHD ($M = 10.24$ years, $SD = 1.56$). The ADHD and control groups did not differ with respect to age, $t(63) = .672, p = .504$.

The parents of all participants filled out the Computerized Diagnostic Interview Schedule for Children Version IV (CDISC-IV; Shaffer & Fisher, 1997; Shaffer, Fisher, Lucas, & Corner, 2003) as well as a history form including questions about developmental and medical history and possible learning disabilities.

The children with ADHD were considered for the study based on two criteria: (1) an existing ADHD diagnosis by a psychologist, psychiatrist, paediatrician, or physician; and the diagnosis of ADHD confirmed on the CDISC-IV; or (2) a diagnosis through the psychology clinic at the Univer-

sity of Victoria, BC, Canada, which included a non-structured interview of parents, clinical observations, teacher/parent rating scales, and neuropsychological assessment. All children in the ADHD group were required to discontinue stimulant medication at least 24 hours prior to participating in the study. Children qualified as suitable controls only if they did not meet diagnostic criteria for ADHD according to the CDISC – IV and if they did not have a history of significant developmental, neurological, and behavioural problems, or a history of significant falls or head injury. All children were recruited through flyers mailed to local schools, advertisements in local magazines, and brochures sent to local physicians

Measures

Executive control

Inhibitory Control

Two different versions of a computerized go/no-go task based on the go/no-go paradigm (e.g., Iaboni, Douglas, & Baker, 1995; Shue & Douglas, 1992), designed to tap the child's ability to inhibit a prepotent motor response, were used in Study I, II, and III. In the first version of the task (Study I and II), the children were instructed to respond as quickly as possible by pressing the spacebar on the computer keypad each time a "go" stimuli (a square with an X, a square with a short vertical line in the middle, a square with a diagonal to the right and a square with a diagonal to the left) appeared on the screen, and to inhibit the response when a "no-go" stimulus was presented (a square with a long vertical line in the middle). The task consisted of a total of 100 trials, and in order to develop a prepotent response (a response habit), the majority of the trials (75%) consisted of go targets. Scoring was based on the number of commission errors (incorrectly responding to a "no-go" stimulus) and omission errors (failing to respond to a "go" stimulus). Reaction time was measured to go stimuli (correct responses) and formed the variable go/no-go RT.

The second version of the go/no-go task (Study III) included two parts and consisted of a blue square, a blue triangle, a red square, and a red triangle presented one at a time on a computer screen. During the first part of this task, the children were instructed to press a key ("go") when a blue figure appeared on the screen, but to make no response ("no-go") when a red figure appeared. The same stimuli were used for the second part of the task, but the children were then instructed to press a key every time they saw a square,

and to inhibit their response every time they saw a triangle, irrespective of color. Altogether the task included 60 stimuli with a “go-rate” of 77%. Thus, prepotency within the task was again provided by making the majority of the stimuli “go-targets”. The score derived from the task was number of commission errors (pressing the key when a “no-go” target was presented).

A computerized Stroop-like task (Gerstadt, Hong & Diamond, 1994) was used in Study I, II, and III to measure interference control. The classic Stroop task (Stroop, 1935) requires individuals to name the color of the ink a word is printed in while inhibiting reading the meaning of the word (e.g., the word “green” might be printed in blue ink). Stroop interference (the Stroop effect) occurs when automatic word reading interferes with the processing of ink color when the word and ink color are incongruent. Because the classic Stroop task requires proficient reading skills in order to validly tap interference control (e.g., MacLeod, 1991), the Stroop-like task in the current studies was a modified version of Gerstadt’s “Day-Night” Stroop (Gerstadt et al., 1994), which does not require reading skills. This task was originally used with one picture pair (day-night), in which conflict was provided through the demand to say the opposite to what is shown on the picture (i.e., to say night when the picture day is shown on the screen). To avoid the ceiling effect that has emerged on this task by the age of 6 years (Passler, Isaac & Hynd, 1985) and to make it more challenging across the ages of 6-13 in Study I and II, four different picture pairs (day-night, boy-girl, large-small and up-down) were used. In order to make this task developmentally sensitive for preschool children, only 2 picture pairs were included (day-night and boy-girl) in Study III. The children were presented with the pictures one at a time on the computer screen and were instructed to say the opposite to what they saw on the screen as quickly as possible (e.g., to say boy when a picture of a girl was shown). The primary index of interference - control was “corrected errors” (initially naming the picture presented on the screen, but correcting oneself to say the opposite). The number of “corrected errors” for each condition was totaled to provide a summary score: total number of “corrected errors” (see Article I and II for a more detailed description of scoring).

The Stroop Color-Word Test (Golden, 1978) was used in Study IV. This test consists of three sections. In the first section, the children were given a sheet of paper in which color words (blue, red or green) were written in black ink. They were instructed to read aloud and in order the words down the columns as quickly as possible, without making mistakes. In the second section, the children were given a sheet of paper on which strings of Xs (i.e., XXXX) were printed in red, blue, or green ink. They were instructed to read aloud the colors as quickly as possible down the columns on the page. In the third section, participants were given a sheet of paper in which color words (red, blue, or green) were written in different colored ink (red, blue, or

green). They were instructed to read aloud the color of the ink the words were printed in, ignoring the word. Participants were given 45 seconds for each section. An interference score was calculated by subtracting the color-word condition from the score on the color condition. The score was used as a measure of the type of inhibitory control referred to as interference control.

A computerized continuous performance test CPT (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) was used in Study I and II. The CPT paradigm requires maintenance of vigilance and inhibition of responses to competing stimuli over a prolonged period of time. In the current version, five different stimuli were included: a square with an X, a square with a short vertical line in the middle, a square with a long vertical line in the middle, a square with a diagonal to the right and a square with a diagonal to the left. The child was instructed to press a response key as quickly as possible every time a cue stimulus (a square with an X) was immediately followed by a target stimulus (a square with a vertical line), while inhibiting responses to any of the other stimuli (the target rate was 25%). Scoring was based on the number of commission errors (incorrectly responding to a non-target) and omission errors (failing to respond to a target). Reaction time was measured for correct responses and formed the variable CPT RT (for a more detailed description on scoring procedures, see Article I and II).

The Statue subtest from the NEPSY battery (Korkman, Kemp, & Kerk, 1998/2000) was used to assess interference control in the form of resistance to distractions outside the task (Study III). It assesses the capacity to sustain a position and to inhibit motor responses to distracters. The child is to maintain a body position and remain silent, with closed eyes, during a 75-sec period, while the examiner tries to provoke reactions by producing sounds (e.g., dropping a pencil on the table, knocking on the table, or coughing). Movements and vocalizations in response to distractions as well as spontaneous reactions are recorded throughout the 75-sec period. The score is the number of 5-sec intervals in which the child is able to stand still, with his or her eyes closed, and keep silent (maximum 15 points).

The Knock and Tap subtest from the Developmental Neuropsychological Assessment Battery (NEPSY; Korkman et al., 1998/2000) was used to assess within-task interference control of a motor response (Study III). In this task, the child is instructed to knock on the table when the examiner taps on the table, and to tap on the table when the examiner knocks on the table. In a second task, the child is to tap with the side of his/her fist when the examiner knocks with his/her knuckles and vice versa, and not to respond at all when the examiner taps with the palm. The score is the total number of correct responses (maximum 30 points).

The Inhibitory Conflict task was used in Study IV. This computerized task was designed to evaluate the ability to ignore irrelevant but prepotent stimulus characteristics (i.e., location or color cues) and to inhibit inappropriate motor responses and respond to specific target stimuli. Participants were required to make responses on a button bar consisting of a large blue button to the left of center and a large green button to the right of center. The stimuli consisted of blue or green blocks appearing on the left or right of the computer screen. There were 80 randomized stimulus items consisting of 20 green blocks on the left, 20 green blocks on the right, 20 blue blocks on the left, and 20 blue blocks on the right, appearing randomly, one at a time, on a black computer screen. In the first condition of this task, participants were asked to press the button that was the same as a particular stimulus attribute (either on the same side or the same color), while ignoring the other stimulus attribute (color or side, respectively). In this task condition, the prepotent stimulus attribute to be ignored conflicts with the correct response, thus creating a stimulus selection conflict. In the second condition of this task, participants were asked to press the button that was opposite to a particular stimulus attribute (color or side), again while ignoring the other stimulus attribute. In this condition, the stimulus attribute does not conflict with the correct response. A response selection conflict is created by having the participant respond opposite to their prepotent same response. The percentage of errors was calculated across the two conditions, stimulus selection and response selection, and was used as a measure of prepotent response inhibition.

Working Memory

In Study I and II, the K-ABC Hand Movements Test from Kaufman's Assessment Battery for Children (Kaufman & Kaufman, 1983) was used as a measure of nonverbal working memory. This task requires the child to hold information active in mind by imitating sequences of hand movements produced by the experimenter. The trials involved series of three different hand movements (side, fist and palm) that became progressively extended (ranging from 2 to 6 movements) and thus more complex. Scoring is based on the mean number of correct sequences across the 20 trials.

Non-verbal working memory was also tested in Study I and II through a time reproduction task (Cappella, Gentile & Juliano, 1977), which measures subjective sense of time and requires rehearsal in working memory. The children were presented with time intervals of 12, 24, and 36 seconds in a mixed order, by the experimenter shining a flashlight. They were then asked to reproduce the time duration as closely as possible. Scoring was based on the mean deviation score, consisting of the absolute discrepancy score be-

tween the children's actual production time and the time presented by the experimenter across the six trials. This was used as a measure of non-verbal working memory.

The Digit span subtest WISC-III (Wechsler, 1992/1994) was used as a verbal working memory task (Study I and II). In this task, the experimenter reads series of "blocks" of digits (ranging from 2 to 9 digits) to the child. The child is then asked to repeat every block of digits in exactly the same order in which it was read (Digit span forward) or in the opposite order (Digit span backwards). Both subtasks require verbal information to be held in mind across delay intervals, and the latter subtask imposes a demand for organizing the material in some way to facilitate responding, abilities typically defined as being involved in working memory. Scores consisted of the average points across the total trials on Digit Span forward and Digit Span backward, respectively.

In Study III, a modified version of the Digit Span subtest of the Wechsler Intelligence Scale for Children, 3rd version (WISC-III; Wechsler, 1992/1994) was used. This involves the experimenter reading series of unrelated nouns (e.g., flower, dog, chair), rather than digits to the child. The child is then asked to repeat every block of words in exactly the same order in which it was read or in the opposite order (Word Span Forward or Backward, respectively). Both measures were used to indicate verbal working memory, with Backward Span presumably representing a higher level of difficulty (cf. Engle, Tuholski, Laughlin, & Conway, 1999). The total points across all trials were obtained for forward and backward span, respectively.

In Study III and IV, two different versions of a computerized spatial working memory task (Pig House) were used. In this task, the children were presented with a matrix on the screen, depicting a house containing 16 windows. The children were informed that pigs would look out of the windows and that the goal of the task was to try to repeat the sequence by pointing to the windows corresponding to the ones in which the pigs had been previously shown. In Study IV, the children were required to repeat the sequence on a touch screen in the exact same order as the original presentation, whereas in Study III the preschool children were simply required to repeat the correct locations, irrespective of order. One point was awarded for each correctly identified location, and the total number of points was used as a measure of visuo-spatial working memory.

The letter number sequencing (LNS) a subtest from the WISC- IV battery (Wechsler, 2003) was used in Study IV as a measure of verbal working memory. In this task, the children are orally given sequences of intermingled letters and numbers. The children are required to repeat the numbers first in

numerical order, and then the letters in alphabetical order. The task consists of 10 items, with each item consisting of three trials ranging from 2-8 intermingled letters and numbers. The test is terminated when the child fails all three trials on any of the levels. Number of correct responses on this task, 30 being the maximum, was used as a measure of verbal working memory.

In Study IV, a modified version of a visuo-spatial working memory game by Owen and colleagues (1990, 1996) was used. In this computerized task, the stimuli consisted of a number of boxes presented on a computer touch screen (see Figure 2). The children were instructed to search through the boxes by touching them one at a time so that they would open and reveal the money hidden inside each box, indicated by a dollar sign (\$), a money token. The children were informed that the goal of the task was to collect all of the money tokens hidden inside the boxes and to fill up an empty column at the side of the screen, which was consecutively filled up each time a money token was found. The key instruction was that once a money token had been found in a particular box, that box would never again be used to hide a token, instead the token would be hidden inside one of the other boxes so that all the boxes on the screen would contain the money once. Thus, on each trial, the total number of money tokens to be found on each trial was consistent with the number of boxes on the screen. The task was initiated by a practice session with two trials consisting of four boxes, followed by the experimental session consisting of two trials at each level with six, seven, eight and nine boxes. The task was scored as total number of errors on each trial, which consisted of the number of times the participant returned to a box in which a money token already had been found. Total number of errors across the 4 levels was considered as a measure of visuo-spatial working memory.

A computerized version of the Self-Ordered Pointing Task (SoP: Peptrides & Milner, 1982) was used in this study. In this task, the children were presented with four series of pictures containing 4, 6, 8, 10, and 12 nameable objects (e.g., finger, squirrel, candle, wagon, etc.) on the computer screen (see Figure 2). The number of presentations within one series corresponded to the number of objects on the screen, and with each presentation the position of the objects would vary. The key instruction for this task is to point to a different picture with each presentation until all the objects within one series have been pointed to. The children were further instructed that they were not allowed to point to the same position twice in a row, and that they were not allowed to say the name of the object out loud. The average number of errors was calculated across the four series (i.e., the number of times an object was pointed to twice) and was considered as a measure of visuo-spatial working memory.

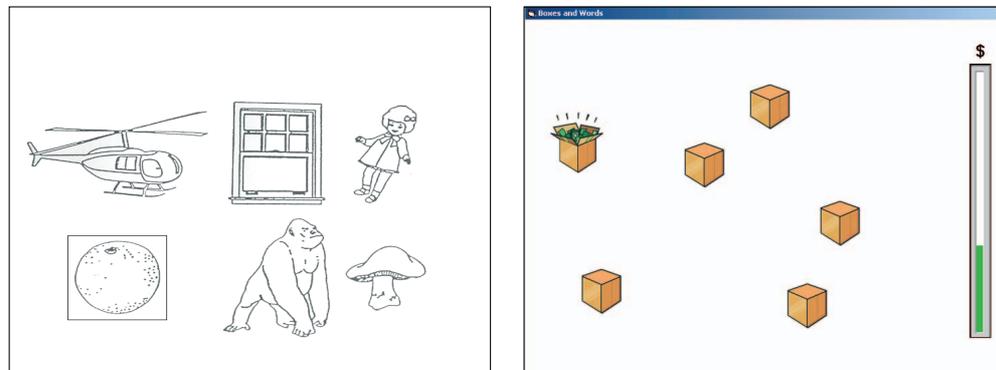


Figure 1. Examples of picture stimuli presented in the Visuo-spatial working memory game and in the Self-ordered pointing task (SoP)

Fluency

Controlled Oral Word Association Test (COWAT) (Gaddes & Crockett, 1975) was used as measure of verbal fluency/reconstitution in Study I and II. The task is divided into two parts: semantic and phonemic fluency. In the semantic fluency task, the child is asked to generate as many animals and things to eat as possible, with a time constraint of 1 minute for each category. In the phonemic fluency task, the child is asked to generate as many words as possible beginning with the letters F, A, and S, with a time constraint of 1 minute per letter. In addition to tapping strategy employment and the generation of ideas, the latter task also demands phonological awareness. The words must be selected according to the following rules: No words must begin with a capital letter, and each word must be used only once. Scoring was based on the “total number of animals generated”, “total number of things to eat generated” and “total number of words generated” across the three letter trials. A mean score was calculated across the semantic and phonemic parts and used as a measure of reconstitution.

Intelligence

In Study II, the children were individually administered the Block-design subtest from WISC-III (Wechsler, 1991). All children were shown to perform within the normal range. IQ was also measured in Study III, again using the Block Design and also the Information subtests from the WISC-III (Wechsler, 1992/1994). These subtests have been shown to correlate highly

with the full-scale IQ (Block Design: $r = .93$; Information: $r = .95$; Groth-Marnat, 1997). An aggregated measure of standard scores (i.e., the raw scores corrected for the child's chronological age) on the Block Design and the Information subtests was used as a measure of intelligence.

Problem Behaviors

ADHD symptoms

In Study II and III, a questionnaire containing items from the DSM-IV criteria for ADHD (APA, 1994) was used to measure hyperactivity/impulsivity and Inattention. This measure has been well validated and is frequently used within ADHD research (e.g., DuPaul, Power, Anastopoulos, & Reid, 1998). The first 9 items of the scale are designed to assess inattention (e.g., often fails to give close attention to details or makes careless mistakes in schoolwork, work or other activities, is often forgetful in daily activities). The next 6 items are designed to assess hyperactivity (e.g., often fidgets with hands or feet or squirms in seat, is often "on the go" or often acts as if "driven by a motor"). The last 3 items are designed to assess impulsivity (often blurts out answers before questions have been completed, often has difficulty awaiting turn). In Study II, only teacher ratings were used and each item was scored on a 3-point scale ranging from 0 (Does not apply) to 2 (Does apply). Cronbach's alpha was .90 or higher for all of the three ADHD subscales. In Study III, both parent and teacher ratings were used and each item on the ADHD scales was scored on a 4-point scale ranging from 0 (never/seldom occurring) to 3 (very frequently occurring). Cronbach's alpha was high, with coefficients ranging from .87 to .97. Mean scores across parent and teacher ratings for ADHD at Time 1 as well as for ADHD at Time 2 were used in the analyses.

In Study II, hyperactivity was also measured through the 10-item version of the Abbreviated Teacher Rating Scale – ATRS (Conners, 1990). The first 6 items (e.g., restlessness, impulsive, constantly moving around) of the scale were used in this study as a recent factor analysis (Parker, Sitarenios, & Conners, 1999) identified these as reflecting hyperactivity/impulsivity. Each item was scored along a four-point dimension ranging from 0 (does not apply at all) to 3 (applies very well). Cronbach's alpha was .93.

In Study II, teachers rated the children on the Edelbrock Child Assessment profile (CAP), which is a subscale including items from the original Child Behavior Checklist (CBCL; Achenbach & Edelbrock, 1983). The CAP includes 7 items of the inattention scale (e.g., fails to finish things he/she

starts, can't concentrate) and five items from the Overactive scale (e.g., talks too much, easily distracted) of the CBCL Teacher form that have the highest loadings on these factors, respectively. Cronbach's alpha was .88 for both the inattention and the overactive subscale.

ODD-symptoms

In Study III, the DSM-IV criteria for Oppositional Defiant Disorder (ODD; APA, 1994) were used. Each item on the ODD scales was scored on a 4-point scale ranging from 0 (never/seldom occurring) to 3 (very frequently occurring). Internal consistency as measured by Cronbach's alpha was high with regard to parent and teacher ratings of ODD, with coefficients ranging from .87 to .97. Because of a weak correlation between parent and teacher ratings for ODD at Time 1 ($r = .33$), these particular scales were analyzed and used separately in the analyses. Mean scores across parent and teacher ratings for ODD at Time 2 were used in the analyses.

Conduct problems and Internalizing problems

The Swedish version of the Rutter, Tizard, and Whitmore (1970) Children's Questionnaire (CBQ) (Teacher's version) was used to measure conduct and internalizing problems in Study II. The CBQ has been used successfully on Swedish schoolchildren (e.g., Berlin, Bohlin, & Rydell, 2002). Internalizing problems (e.g., often worried, rather solitary) are assessed by five items, and conduct problems (e.g., often disobedient, often tells lies) are assessed by seven items. Each item was scored along a five-point dimension ranging from 1 (do not agree at all) to 5 (totally agree). Cronbach's alpha was .88 and .86 for the two scales, respectively.

Study I

“Executive Functions in Children Aged 6 to 13: A Dimensional and Developmental Study”

Background and aims

Growing evidence now suggests that ADHD is best viewed as a developmental delay in normal, ongoing neurodevelopmental processes (e.g., Brown et al., 2001; Levy et al., 1997). This dimensional view of ADHD emphasizes the importance of knowledge regarding the normal development in neuropsychological processes predicted to be involved in the etiology of ADHD. Such data will improve our understanding of the role of EF in ADHD and eventually result in more effective therapeutic treatments for this complex disorder.

The aim of this study was therefore to expand our knowledge on the normal development of basic executive components by addressing specific problems that have limited interpretation of findings in past research. Most previous studies have been guided by the construct of EF derived from the adult neuropsychological literature, rather than on functions relevant to theories within a developmental framework. Therefore, measures based on developmentally relevant conceptualizations of executive control (Barkley (1997a, b; Roberts & Pennington, 1996) were used. These measures were then subjected to factor analysis and developmental analysis was conducted on the derived executive components. Thus, age and sex effects were studied at the level of EF domains rather than on results derived from specific EF tasks.

Results

First, a principal component factor analysis with age as a covariate was conducted based on the total sample. Size of the interfactor correlation ($r = -.12$ to $-.15$) favored an orthogonal rotation, and in interpreting the factors, loadings greater than .30 were considered salient. Three independent factors interpreted as Disinhibition, Speed/Arousal, and WM/Fluency were identified (see Table 1). Second, age and sex differences for the delineated functions were assessed through a multivariate analysis of variance (MANOVA).

Age-dependent changes in children's performances on all three dimensions were demonstrated (see Table 2 & Figure 3), whereas sex differences were found only for the Speed/Arousal dimension ($F(4, 81) = 3.57, p < .0001$).

Table 1. *Principal components factor structure of EF measures based on the total sample (n=92), with age as a covariate*

<i>Measures</i>	<i>I: Disinhibition</i>	<i>II: Speed/Arousal</i>	<i>III: WM/Fluency</i>
CPT disinhibition	.87	.07	-.18
CPT impulsivity	.80	.05	.12
CPT inattentive impulsivity	.63	-.12	.01
Go/no-go commissions	.38	-.07	-.27
Go/no-go RT	-.17	.80	-.18
CPT RT	-.12	.73	-.01
CPT omissions	.11	.39	.04
Go/no-go omissions	-.01	.38	-.22
Digit span forward	-.03	-.01	.49
Verbal fluency (COWAT)	-.00	-.10	.48
Digit span backward	-.13	-.09	.40
Hand movements	-.20	-.16	.40
Stroop	.20	-.23	-.41
Time reproduction	-.02	-.10	-.43
Factor eigenvalues	2.12	1.72	1.39

Note. CPT: Continuous Performance Test; RT: Reaction Time: Loadings $\geq .30$ were considered as salient. Negative loadings on factor 3 reflect that a lower score index better performance.

Table 2. *Standardized mean factor score by age group and significance tests of developmental effects*

<i>Factor</i>	<i>Age Group</i>								<i>F</i>	<i>Effects</i>
	<i>1</i>		<i>2</i>		<i>3</i>		<i>4</i>			
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
I: Disinhibition	0.07	0.51	0.20	0.69	-0.10	0.49	-0.17	0.35	2.17	1, 2 > 3, 4*
II: Speed/Arousal	0.38	0.53	-0.01	0.37	-0.07	0.38	-0.29	0.29	2.91	1 < 2, 3, 4**
III: WM/Fluency	-0.30	0.24	-0.01	0.24	0.09	0.15	0.27	0.22	6.05	1 < 2, 3, 4** 2, 3 < 4*

* $p < .05$. ** $p < .01$.

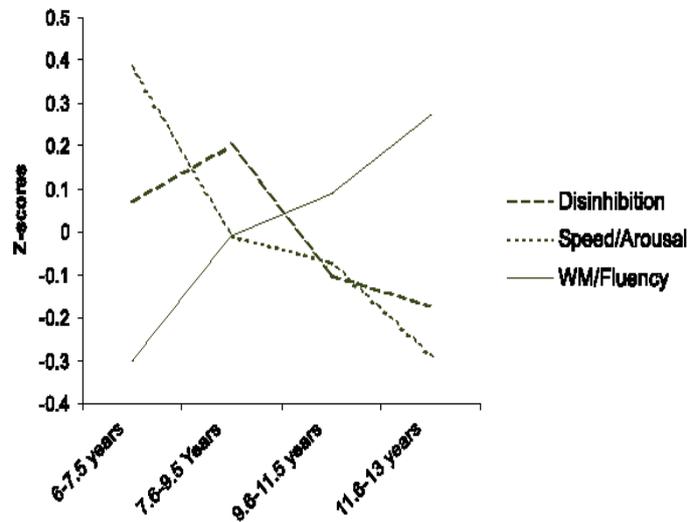


Figure 3. Standardized mean score on the Disinhibition, Speed/Arousal and Wm/Fluency factors as a function of age.

Conclusions

The factor analysis revealed three executive dimensions labeled Disinhibition, Speed/Arousal, and WM/Fluency. The Disinhibition dimension included scores from various inhibitory variables that merely required a response to be withheld. Interestingly, the Stroop-like task thought to measure the type of inhibition referred to as interference control, and which not only requires a response to be withheld but also that a shift to a new response is made, loaded on the WM/Fluency dimensions. This finding is important in that it underscores the importance of distinguishing between different types of inhibitory control in childhood cognition and that various types of inhibitory control may share underlying variance with working memory processes to different extents. The Speed/Arousal factor was interpreted to reflect a deficit in self-regulation of arousal and motivation to meet situational demands. The existence of such a dimension is in line with the idea that the ability to regulate arousal is an important aspect of task performance (Barkley, 1997b).

The data showed different developmental patterns depending on type of executive function. The dimension interpreted as Speed/Arousal seemed to

be the first one to reach maturity, with the most active period of development occurring around the age of 8. The “withholding” dimension of inhibition revealed maturity around age 10, along with the first developmental spurt on the WM/Fluency factor. The second developmental spurt on WM/Fluency indicates protracted development into adolescence. It may be concluded that the developmental data obtained in this study converge with previous developmental studies of executive functions in that there appear to emerge three stages of maturation: early childhood (6–8 years of age), middle childhood (9–12 years of age) and adolescence.

Overall, the results support the view of inhibitory control and working memory as two salient aspects of efficient EF (Barkley, 1997 a, b; Roberts & Pennington, 1996). Knowledge of structural organization of EF in childhood and of the normal age-related change in executive processes should be important in analyzing and understanding executive impairments in ADHD, particularly when asking whether ADHD represents the extreme of a dimension that applies to everyone, or a category of its own.

Study II

“Developmental Change in the Relation between Executive Functions and Symptoms of ADHD and Co-occurring Behavior Problems”

Background and aims

The classical notion of ADHD as a static disorder is now giving way to a new perspective that highlights ADHD as a developmentally relative deficit, in which the expression of ADHD symptoms undergoes change with age (i.e., the developmental hypothesis; Barkely, 2003). Indeed, symptoms of hyperactivity have mostly been observed in younger children and shown to decrease with age, whereas symptoms of inattention have been found to be more stable across childhood (Hart et al., 1995). Extant research has not effectively examined the effect of age on the relation between neuropsychological processes shown to be impaired in ADHD and typical behavioral symptoms associated with the disorder. Such data should constitute an important step toward a more well-founded understanding of the ADHD construct as a developmentally relative deficit. This study investigates the effect

of age on the relation between behavioral symptoms associated with ADHD (cardinal as well as co-occurring) and executive functioning, from a framework that conceptualizes ADHD as a developmental delay in normal ongoing processes rather than as a categorical disorder.

Data reduction

The hyperactivity and impulsivity items of the DSM-IV criteria for ADHD, the hyperactivity items of The Connors Teacher Rating Scale and the hyperactivity items of the the Edelbrock CAP were aggregated to form the variable hyperactivity/impulsivity, with a total of 20 items and an internal consistency of $a = 0.96$. Similarly, the inattention items of the DSM-IV criteria for ADHD and the inattention items of the Edelbrock CAP were combined to form the variable inattention, with a total of 16 items and an internal consistency of $a = 0.94$. All other behavioral measures (conduct problems and internalizing problems) were kept according to their original scales.

To reduce the number of EF variables to the level of components, the current statistical analyses were based on results from a previous principal factor analysis of the entire sample with age as a co-variate. The items comprising the third dimension were quite heterogeneous; both verbal and non-verbal working memory and fluency, even the Stroop-like task, which usually is considered an inhibition-related measure, loaded on the working memory/fluency dimension. Therefore, it was of interest in the current study to divide this dimension into three purer construct subscales, so that differences regarding verbal and nonverbal working memory measures in relation to behavior problems could be detected. Consequently, the former working memory/fluency dimension was divided into: 'non-verbal working memory' (hand movements and time reproduction), $a = 0.60$, and 'verbal working memory/fluency' (digit span backwards and forwards), $a = 0.77$. It was decided to let the Stroop-like task stand alone in the current statistical analysis (see Paper I for a more extensive account of the factor analytic results).

Results

Regression analyses were performed to investigate age effects on the relation between the executive measures and the behavioral measures. Age group, sex and each executive measure were used as predictor variables and the various behavioral measures as outcome variables. In order to investigate age effects, interaction terms were formed between age group and each of the executive measures and added to the equation in separate analyses (see Aiken & West, 1996). Regression analyses were also performed to investigate the predictive relations between the executive measures and behavioral problems, for the total sample. For results regarding age effects on the rela-

tion between the cognitive measures and behavioral problems, see Table 3.

Table 3. Beta weights (*b*) obtained from the regression analysis relating the executive measures and the behavioral measures, for age group 1 (*n*=48) and age group 2 (*n*=44), with age and sex as co-variates

	Hyperactivity/ impulsivity	Inattention	Internalizing problems	Conduct problems
<i>Disinhibition</i>				
Age group 1	0.45**	0.32**	0.00	0.08
Age group 2	0.04	0.05	0.07	0.06
<i>Speed/arousal</i>				
Age group 1	0.12	0.20 [†]	-0.15	0.07
Age group 2	-0.09	-0.33* [†]	0.03	0.01
<i>Verbal WM/fluency</i>				
Age group 1	0.11	0.11	-0.21	0.07
Age group 2	-0.12	-0.30* [†]	-0.23	0.00
<i>Non-verbal WM</i>				
Age group 1	-0.17	-0.09	-0.42**	-0.09
Age group 2	-0.07	-0.25 [†]	0.00	0.02
<i>Stroop-like task</i>				
Age group 1	-0.21	-0.15	0.04	-0.05
Age group 2	0.12	0.19	0.30* [†]	0.07

WM: working memory.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

[†]Significant age effect ($p < 0.05$) on the relation between the particular cognitive measure and behavioural measure.

With regard to results for the total sample, disinhibition was significantly related to hyperactivity/impulsivity, $\beta = 0.23$, $p = 0.03$, indicating that the children who showed poor performance on the executive measures tapping inhibition were rated as high on hyperactivity/impulsivity. No other executive measures were significantly related to hyperactivity/impulsivity.

A tendency toward significance was obtained for the total sample, both between verbal working memory/fluency and inattention, $\beta = 0.24$, $p = 0.08$, and non-verbal working memory and inattention, $\beta = 0.21$, $p = 0.09$. A tendency toward a significant relation was also obtained for the total sample between disinhibition and inattention, $\beta = 0.18$, $p = 0.09$, again indicating that those children who showed poor performance on the inhibition measures were rated as high on inattention. Speed/arousal did not predict levels of inattention for the total sample, $\beta = 0.05$, $p = 0.67$. Both verbal working memory/fluency and nonverbal working memory related significantly to

internalizing problems in a negative direction for the total sample, $\beta = 0.45$, $p = 0.001$, $\beta = 0.36$, $p = 0.006$, respectively, demonstrating that children who showed poor performance on the measures tapping verbal working memory/fluency as well as non-verbal working memory were rated as high on internalizing problems. When controlling for hyperactivity/impulsivity and inattention, the relation between the two working memory measures and internalizing problems were still significant, indicating that the relations were independent of these behavioral problems. No significant relations were obtained between any of the executive measures and conduct problems.

Conclusions

The results concerning the developmental pattern (see Table 3) were largely in accordance with the predictions that disinhibition would be most clearly related to ADHD symptoms among young children, whereas for the older children, later developing and more complex executive functions such as working memory and fluency would relate to ADHD symptoms, particularly problems with inattention. The results provide some support for the view that poor inhibition is a neuropsychological characteristic associated with ADHD symptoms also in normal groups, particularly for younger children. One explanation for this may be that inhibitory capacity matures early and reaches adult levels by the age of 8–12 years (e.g. Brocki & Bohlin, 2004; Passler et al., 1985; Welsh et al., 1991), whereas studies have found working memory functions to appear relatively early but to develop over time, reaching greater complexity around 13–15 years of age (e.g. Brocki & Bohlin, 2004; Levin et al., 1991; for a review see Korkman et al., 2001). Taken together, the results are in line with Barkley's developmental EF model, in that associations between ADHD symptoms and EFs such as working memory, set-shifting, and reconstitution (as opposed to inhibition) would appear later on during the school period.

In sum, our study is one of the very first to examine age effects on the relation between EF and ADHD behavioral problems. Indeed, the obtained data show the promise of the developmental perspective of ADHD, by showing that distinct types of executive components are linked to ADHD symptoms at different developmental stages. Further, the results showing linear associations between the two ADHD symptom domains and executive function add further support to available research describing the nature of ADHD as a continuous dimension with variable expression throughout the general population.

Study III

*“Early Concurrent and Longitudinal symptoms of ADHD and ODD:
Relations to different types of Inhibitory Control and Working Memory”*

Background and aims

Executive control involves a complex collection of cognitive processes that are critical for the execution of goal-directed behavior. Deficits in such executive processes appear to be one of the important components of the causal neuropsychology of ADHD (e.g., Castellanos et al., 2006; Willcutt et al., 2005). Albeit not as consistent, executive control deficits have also been found in Oppositional Defiant Disorder (ODD) and Conduct Disorder (CD) (e.g., Oosterlaan, Logan, & Sergeant, 1998; Moffitt, 1993; Séguin, Boulerice, Harden, Tremblay, Phil, 1999), suggesting that impairment in executive control is not a unique marker for ADHD. However, most previous studies have focused on elementary school-aged children and have not included longitudinal data. This study investigates the influence of different types of inhibitory control and working memory processes on concurrent and 2-year longitudinal symptoms of ADHD and ODD in a preschool sample including children at risk for developing ADHD and/or ODD.

Preliminary analysis

All analyses throughout this study are presented using age and social background as covariates. Table 5 shows the inter-correlations between the measures of inhibitory control, working memory and IQ. A moderate to strong positive correlation was obtained between the Stroop-like task and the Knock and Tap task. Therefore, these two measures were standardized and averaged, and the aggregated score is used to indicate interference control within task. Attrition for specific measures varied between one and five children, due to some children failing to complete a specific task.

Table 5. Inter-correlations between the inhibition and working memory measures, controlling for age and social background. $N = 66-72$

<i>Measures</i>	IQ	Stroop - Task	Knock and Tap	Statue	Interf. w. task ^a	Go/ No-go (com.)	Pig house	Word Span F.	Word Span B.
IQ	-	.31**	.30*	.35**	.35**	-.15	.21	.22	.32**
Stroop-Task		-	.53***	.17	.88***	-.14	-.07	-.10	.32**
Knock and Tap			-	.34**	.89***	-.13	.03	.20	.22
Statue				-	.25*	-.16	-.12	-.19	.13
Interf.w.task ^a					-	-.19	-.00	.12	.31**
Go/No-go(com.)						-	-.10	-.22	-.03
Pig House							-	.07	.12
Word Span F.								-	.19
Word Span B.									-

* $p < .05$, ** $p < .01$, *** $p < .001$

Note: $N = 61-66$ for analyses with IQ. com = commissions, F = forward, B = backward.

^a Interference within task = Standardized and aggregated measure of the Stroop-like and Knock and tap tasks.

Results

The concurrent and longitudinal relations between the EF measures and ADHD and ODD symptoms, adjusted for age and social background, are presented in Table 6. Figures within parentheses in Table 6 represent the relations adjusted for comorbid ODD and ADHD symptoms, respectively. Overall, the results showed that the three types of inhibitory control were significantly related to current and 2-year longitudinal symptoms of ADHD and that these relations remained when adjusting for symptoms of ODD. Inhibitory control was also related to symptoms of ODD both concurrently and longitudinally, however when adjusting for symptoms of ADHD, these relations no longer remained. No significant relations were obtained between working memory and symptoms of ADHD or ODD, either concurrently or longitudinally.

Table 6. *Correlations Between Time 1 Inhibition and Working Memory Measures and Time 1 ADHD and ODD Symptoms and Time 2 ADHD and ODD Symptoms, Controlling for Age and Social Background. Figures within Parentheses Represent the Relations Controlling for ADHD and ODD Symptoms Respectively. N = 66 -72*

	ADHD Symptoms T1	ODD ^a Symptoms T1	ADHD Symptoms T2	ODD Symptoms T2
<i>Inhibition</i>				
Interference Ctrl (Within Task)	-.41***(.27*)	-.39***(-.12)	-.48***(-.41**)	-.30*(.10)
Interference Ctrl (Outside Task)	-.53***(.48***)	-.33*** (.09)	-.45***(-.45**)	-.21(.22)
Prepotent response inhibition	.36***(.23 ^b)	.33***(.10)	.39** (.27*)	.29*(.00)
<i>Working Memory</i>				
Spatial WM	-.03 (-.17)	.10 (.19)	-.01(.09)	-.09 (-.13)
Verbal WM (forward span)	-.13(-.03)	-.12 (-.06)	-.15(-.10)	-.11(.00)
Verbal WM (backward span)	-.03 (.00)	-.08 (-.05)	-.13(-.10)	-.08 (.02)

* $p < .05$, ** $p < .01$, *** $p < .001$

Note: WM = Working memory. ^a ODD ratings at T₁ denote teacher ratings only. No significant correlations were obtained between parent ratings of ODD at T₁ and any of the inhibitory control or working memory measures. ^b $p = .07$.

To investigate whether the three types of inhibitory control contributed with common or independent variance in explaining ADHD symptoms at Time 2, these measures were simultaneously entered into a multiple linear regression analysis, with the inhibition measures as predictor variables and the ADHD symptom score as the outcome variable. The regression model was significant, $F(5, 56) = 7.28$, $p < .0001$, $R^2 = .39$, with all three types of inhibitory control predicting ratings of ADHD at Time 2, independent of one another ($\beta_{\text{Interfer.Within.Task}} = -.34$, $p < .01$, $\beta_{\text{Interfer.Outside.Task}} = -.27$, $p < .05$, $\beta_{\text{Prepot.resp.inhib}} = .26$, $p < .05$). Together, interference control within-task, interference control outside task and prepotent response inhibition explained 34% of the variance in ADHD symptoms. When conducting the same multiple regression analysis with control for ODD symptoms, the two types of interference control still made independent contributions, although the effect of prepotent response inhibition was only marginally significant ($p < .09$),

and the explained variance was reduced to 19%. A similar multiple regression analysis was conducted with ODD symptoms at Time 2 as the outcome variable and the inhibitory control measures as predictor variables. The regression model was significant, $F(5, 56) = 2.90, p < .05, R^2 = .21$, with none of the inhibitory control measures contributing with independent variance. Together, the three types of inhibitory control explained 11% of the variance in ODD symptoms at Time 2. A similar pattern of results was obtained when conducting the same multiple regression analysis with control for ADHD symptoms, with none of the inhibitory control measures making independent contributions and the explained variance in ODD symptoms being reduced to 1%.

Intelligence

IQ was significantly related to combined parent and teacher ratings of ADHD symptoms at Time 1 and Time 2, $r = -.44, p < .0001, r = -.32, p < .01$. IQ was also significantly correlated with parent ratings of ODD at Time 1, $r = -.31, p < .01$, and combined parent and teacher ratings of ODD symptoms at Time 2, $r = -.26, p > .01$, but not with teacher ratings of ODD at Time 1, $r = -.09, p > .05$. With regard to correlations among IQ and the inhibitory control and working memory measures (presented in Table 5), significant correlations were obtained between IQ, the Stroop-like task, knock and tap as well as with interference control within task (i.e., composite across the Stroop-like task and knock and tap), interference control outside task (i.e., statue) and verbal working memory (i.e., wordspan backwards). Controlling for IQ when predicting ADHD and ODD symptoms from measures of inhibitory control and working memory did not change the level of significance of contributing variables.

Conclusions

To sum up, our results are supportive of the idea that inhibitory control is an important component of the early neuropsychology of ADHD rather than ODD. Indeed, the results are in line with Barkley's (1997a, b) formulation that ADHD is underpinned by deficits in inhibitory control. Further, the lack of relations between EF and ODD in this study underscores the need for future studies to examine neuropsychological or other factors that may be specifically linked to ODD symptoms. Our results are unique in showing that three distinct inhibitory phenomena – interference control within task, interference control outside task, and prepotent response inhibition – constituted independent predictors in explaining ADHD symptoms 2 years later. This result suggests that several distinct inhibitory processes are associated with early ADHD symptoms. With regard to working memory, no relations to ADHD or ODD symptoms were found. The current findings stress the importance of studying how different types of inhibitory control as well as

working memory may be linked to ADHD symptoms at different developmental stages. Such maturational issues are important, particularly when viewing ADHD as a developmental disorder with underlying neuropsychological components that may vary with a child's age.

Study IV

“Working Memory Function in School-aged Children with ADHD-C: Are Deficits Independent of Inhibitory Control?”

Background and aims

Impaired Executive Functions (EF) constitute one of the typical characteristics of the complex neuropsychological ADHD profile (Nigg, 2006; Willcutt et al., 2005). There is general consensus that working memory (WM) and inhibitory control are the two core EF domains. Indeed, compelling evidence exists for deficits in inhibitory control (and prepotent response inhibition in particular) in ADHD (e.g., Castellanos et al., 2006; Willcutt et al., 2005). In contrast, empirical evidence for ADHD deficits in WM has not been as conclusive (Pennington & Ozonoff, 1996 versus Martinussen, Hayden, Hogg-Johnsson, & Tannock, 2005; Willcutt et al., 2005). Further, robust evidence for impaired inhibitory control in ADHD together with theoretical models suggesting a close interplay between inhibitory and WM processes in adult as well as in developmental cognition (e.g., Barkley, 1997; Hasher & Zacks, 1988; Roberts & Pennington, 1996; Engle & Kane, 2004) raise the question of the relative independence of deficits in WM and inhibitory control in the neuropsychology of ADHD. This study investigates differences between children with ADHD and normal controls on verbal and visuo-spatial WM tasks. The inclusion of two types of inhibitory control – interference control and prepotent response inhibition – also allowed us to explore whether WM deficits in ADHD are independent of difficulties with inhibitory control.

Results

Table 7 provides descriptive statistics and t-tests examining group differences for all WM and inhibitory tasks included in the study. With the exception of non-significant group differences for the SoP and the Stroop-task ($p > .05$), the ADHD group showed lower levels of performance on all other WM tasks and on the inhibitory conflict task ($p < .05$). Further, a large effect size was found for the LNS ($g = .85$), whereas effect sizes in the me-

dium range were found for the visuo-spatial WM game ($g = .60$), the Pig House ($g = .60$) and the inhibitory conflict task ($g = .43$), and small effect sizes were found for the SoP ($g = .21$) and the Stroop-task ($g = .26$).

To investigate whether WM deficits in ADHD are independent of deficits in inhibitory control and to see how well the WM tasks and the inhibitory conflict task could predict group membership, two separate logistic regression analyses were conducted. In the first regression model, the WM tasks for which significant group differences had been found were entered in the first step, $\chi^2(3, N = 63) = 12.6, p < .01, R^2 = .24$, with only the LNS making an independent contribution ($p < .05$). In the second step, the inhibitory conflict task was entered, R^2 change = .04, $p = .08$. In the second regression model, the inhibitory conflict task was entered in the first step $\chi^2(1, N = 63) = 4.0, p < .05, R^2 = .08$, and the WM tasks in the second step, R^2 change = .20, $p < .05$, again with only the LNS making an independent contribution ($p < .05$). Thus working memory seems to contribute with variance over and above that of inhibitory control in explaining the classification of ADHD and control children. Together the WM tasks and the inhibitory conflict task reliably distinguished between ADHD children and controls, classifying 75% of the participants correctly.

Table 8 provides the inter-correlations for the various WM and inhibitory tasks, adjusting for age. With the exception of a non-significant correlation between the pig house task and the SoP, significant relations were obtained between all WM tasks.

Table 7. Group Means, Standard Deviations (SD), *t*-statistics (*t*) and effect-sizes (*g*) for all working memory and inhibitory control tasks included in the study

<i>Measures</i>	ADHD (n=31)		Controls (n=34)		<i>t</i>	ES ^a <i>g</i>
	M	SD	M	SD		
<i>Working Memory</i>						
LNS	14.77	3.58	17.24	2.25	3.33***	.85
SoP (errors)	15.13	6.04	13.75	7.66	.84	.21
Pig House Game	26.26	12.76	33.80	13.84	2.27*	.60
<i>Visuo-Spatial WM</i>						
Game (errors)	35.69	22.79	50.13	25.31	2.38*	.60
<i>Inhibitory Control</i>						
Stroop Task	18.20	5.45	19.63	9.25	.98	.26
InhibitoryConflict Task errors (%)	.12	.08	.08	.06	2.00*	.43

* $p < .05$, ** $p < .01$, *** $p < .001$

Note: The number of participants differs for the dependent variables due to missing data. SoP= Self-ordered pointing task. ^a Hedges (1981) effect size formula (*g*) with pooled standard deviations.

Table 8. Inter-correlations between the WM tasks and the inhibitory control tasks, Adjusted for Age, $N = 57-65$

<i>Measures</i>	LNS	SoP	Pig house	Visuo-spatial WM game	Stroop task	Inhibitory conflict task
LNS	-	-.23*	-.27*	-.41*	.00	.02
SoP (errors)		-	-.11	-.28*	-.14	.14
Pig House			-	-.30*	-.05	-.26*
Visuo-spatial WM game				-	.12	.16
Stroop Task					-	.05
Inhibitory conflict task (errors)						-

* $p < .05$, ** $p < .01$

Note: LNS = Letter Number Sequencing, SoP = Self-Ordered Pointing Task.

Conclusions

Overall, our results are in line with previous findings suggesting impaired verbal and visuo-spatial WM processes in elementary school-aged children with ADHD (e.g., Martinussen et al., 2005). Particular weakness in performance was found for a verbal WM task, thought to put a heavy load on the executive process of the WM system. This result differs from previous findings showing larger impairments in visuo-spatial compared to verbal WM processes in ADHD (Martinussen et al., 2005; Willcutt et al., 2005). Future studies should further evaluate whether discrepancies in results for verbal and visuo-spatial WM deficits in ADHD could be due to task variance in difficulty level or relative load put on the executive component of the WM system, rather than variance in modality. Further, the results from the logistic regression analysis showed that prepotent response inhibition did not contribute to ADHD classification over and above that of WM, whereas the opposite was true for WM. Thus, our findings suggest that although deficits in WM and prepotent response inhibition may represent a common aspect of poor EF in ADHD, there is also a specific contribution of WM that could possibly reflect activation of executive WM processes. Indeed, the extent to which deficits in WM and inhibitory control represent common or independent variance in ADHD symptoms requires further examination. Clever experimental designs that can isolate the WM components (i.e., storage and executive processes) and clarify their relation to different types of inhibitory control should lead to further advances, bringing us closer to answering the question of whether WM deficits are independent of inhibitory control in children with ADHD.

General Discussion

The ultimate aim of the present thesis was to further the understanding of EF in relation to ADHD, with primary focus on structure (i.e., dimensions) and the developmental aspects of these complex cognitive processes. Rooted in a developmental and dimensional perspective on ADHD, the four studies included in the current thesis are based on two theoretical assumptions. First, quantitative delays rather than qualitative deviations in executive control in children with ADHD relative to normal children are assumed. Second, the behavioral and neuropsychological manifestation of ADHD is predicted to vary with a child's maturational stage, rather than being static. The general discussion begins with a summary of rationales and main findings of the current thesis. Thereafter, the results regarding inhibitory control and WM will be discussed in relation to the three central themes of this thesis: Dimensions, Development and ADHD.

The story of the current thesis: Rationales and main findings

As a starting point of my research, I wished to identify the structure of EF in typically developing children. Therefore, a factor analysis on multiple indicators of EF across domains was conducted. Further, to avoid the problem of data reflecting age-related variance idiosyncratic to specific tasks, developmental analyses were carried out on the EF dimensions identified by the factor analysis. Thus, by using factor analysis, we addressed the common problem of low construct validity in EF tasks. The results indicated that inhibitory control and WM are two salient EF components in childhood, with inhibitory control reaching developmental maturation before WM (Study I). The next study was intended to fill a gap in the extant ADHD literature by providing data on age effects on continuous relations between EF dimensions and behavioral symptoms associated with ADHD. First, the results showed that inhibitory control and WM are related to ADHD symptoms in normal children of elementary school age. Second, the findings suggest that poor inhibitory control is primarily linked to hyperactivity/impulsivity and inattention in younger children, whereas that poor functioning with regard to

WM is linked to inattention for older children (Study II). In sum, the data from Study I and II showed that inhibitory control and WM are key components in the development of EF in childhood. Further, the obtained associations between function in these components and ADHD symptoms in a normal sample give support to the dimensional perspective on ADHD. Finally, the unique finding that age moderates the relation between inhibitory control and WM and ADHD symptoms supports the view of ADHD as a developmentally relative deficit.

Based on the findings from Study I and II, we wished to put further focus on studying inhibitory control and WM functions in samples representing higher ADHD symptom severity levels as well as different developmental levels. Study III therefore examined different types of inhibitory control and WM as potential predictors of longitudinal ADHD and ODD symptoms in preschoolers, including children identified as being at risk for developing ADHD and/or ODD. We also wished to examine the specificity of executive weaknesses in preschool ADHD by controlling for ODD, and vice versa, in our analyses. The findings from Study III suggest that deficits in inhibitory control play an important role in the neuropsychology of ADHD rather than that of ODD in the preschool period. Further, the longitudinal findings from Study III are unique in showing that three distinct types of inhibitory control and WM made independent contributions to the explained variance in 2-year longitudinal ADHD symptoms. Interestingly, no associations between WM and preschool symptoms of ADHD or ODD were found in Study III.

Study IV examined group differences between children with ADHD and normal controls of elementary school age in performance on verbal and visuo-spatial WM tasks. Further, we studied the relative independence of WM and inhibitory control in contributing to the explained variance in ADHD classification (ADHD versus controls). Overall, the results suggest a significant weakness in verbal and visuo-spatial WM processes in children with ADHD, with the strongest effect size being found for a verbal WM task, thought to put a heavy load on the executive component of the WM system. With regard to inhibitory control, children with ADHD showed impaired performance on prepotent response inhibition, but not on interference control. Further, findings from logistic regression analyses suggested that deficits in inhibitory control and WM may represent distinct but related cognitive domains in children with ADHD. The results from Study I, II, III, and IV will be discussed in greater detail in the following sections.

Inhibitory control and WM: Important EF dimensions in typical development and in relation to ADHD

In general, the results from Study I, II, III, and IV support the view of inhibitory control and WM as important components of EF in typically developing children and as significant neuropsychological correlates of ADHD symptoms (Barkley, 1997a, b; Roberts & Pennington, 1996). Thus, the initial conclusion with regard to dimensional issues of EF holds that inhibitory control and WM might serve as a sufficient and more parsimonious description of the “unconstrained frontal metaphor” (Pennington & Ozonoff, 1996, p. 6). This means that a more precise understanding of EF should include closer examination of the WM and inhibitory control components, at least with regard to normal development and in relation to ADHD. Indeed, three of the studies included in the present thesis (Study I, III, and IV) provide important information on structural issues of inhibitory control and WM, reflecting the “cognitive” complexity of these two components. These findings will be discussed below.

Study I was designed to evaluate the structure of EF at the level of dimensions, rather than at the level of individual tasks. With reservation for the fact that the outcome of dimensional analysis depends on the number and type of variables included, examination of the factor compositions in Study I reveals complexity, broadness and potential commonality in and between inhibitory control and WM processes. First, in terms of inhibitory control, the analysis demonstrates distinction between different types or sub-processes of this phenomenon. To be more precise, the dimension interpreted as “disinhibition” was comprised of tasks merely demanding that a response be withheld, whereas the Stroop-like task, which is assumed to tap the interference aspect of inhibitory control (e.g., Barkley, 1997a) and which requires a shift to a new response being made, loaded on the factor labeled WM/fluency. This result is in accordance with Pennington’s (1997) differentiation between types of inhibitory control that require the individual to stop and do nothing in its place, and inhibitory control that requires the individual to stop and do something else. Further, variance in magnitude of loadings on the “disinhibition” factor (ranging from .38 to .87) of course indicates common, but also fractionated variance between the different inhibitory tasks. To be more precise, the highest loadings on the “disinhibition factor” came from variables derived from the CPT task, whereas the lowest loading came from commissions on the go/no-go task. Such diversity in loadings between these inhibitory tasks may be taken to reflect differences in prepotency or variations in the ratio of go to no/go stimuli (i.e., when the ratio of no/go to go stimuli is low, a prepotent tendency to respond is produced, making the stopping process more difficult upon presentation of the no/go stimulus). Cer-

tainly, the CPT task did not make the response prepotent in the same sense as did the go/no-go task, which had a target rate of 75%, because in the CPT, only a minority of the stimuli required a response. Thus, prepotency may represent a possible factor contributing to the underlying diversity of inhibitory processes.

The result from the dimensional analysis in Study I also indicates shared variance between inhibitory control and WM. First, the fact that the Stroop-like task loaded on the WM dimension suggests underlying commonality between the type of inhibitory control referred to as interference control, which in this case requires a shift from a prepotent incorrect response to a correct but not prepotent response, and WM processes. Second, although the variable representing commissions on the go/no-go task primarily loaded on the “disinhibition dimension”, it also had a loading (.27) falling just under the level considered as salient (.30) on the WM dimension, indicating some underlying commonality also between prepotent response inhibition and WM.

The findings from Study I stress that although inhibitory processes share common variance, they do not constitute a unitary cognitive phenomenon. In general, these results are consistent with models of ADHD that break down inhibitory control into different types. For example, Nigg (2001) distinguishes between executive inhibition (i.e., effortful or controlled inhibition) and motivational inhibition (cognition associated with reward and punishment), and Barkley (1997a, b) defines behavioral inhibition in terms of three interrelated inhibitory processes: (1) inhibition of a prepotent response (i.e., responses which have been reinforced in the past or within a cognitive task), (2) stopping of an ongoing response and (3) interference control (i.e., distractibility). These theoretical models of inhibitory control are consistent with neuroanatomical findings suggesting that different inhibitory processes are likely to be mediated by distinct cortical areas (e.g., Casey et al., 1997).

Further, the dimensional analysis from Study I showed that particularly interference control and to some extent also prepotent response inhibition seem to share variance with WM. These findings are in line with theoretical models suggesting a close interplay between inhibitory processes and WM capacity (e.g., Kane & Engle, 2002; Engle & Kane, 2004; Hasher & Zacks, 1988; Roberts & Pennington, 1996). It is predicted that these two processes tap the same pool of executive resources and thus share some common underlying mechanism. For example, the relation between these two components has been described as the requirement for inhibitory control to gate out irrelevant information from the mental workspace of WM and to delete no longer relevant information from that limited-capacity workspace (Hasher & Zacks, 1988).

In light of previous evidence suggesting that inhibitory control and WM are important components of the complex neuropsychology of ADHD (e.g., Castellanos et al., 2006; Willcutt et al., 2005; Martinussen et al., 2005), the results just discussed motivate deconstruction of and further research into the role of different types of inhibitory control and WM processes in relation to ADHD during different age periods. Examination of the independence of inhibitory control and WM deficits in ADHD should also be of relevance in furthering our understanding of the neuropsychology of this disorder.

Deconstruction of the inhibitory phenomenon in relation to ADHD

Regarding deconstruction of the inhibitory control phenomenon in relation to symptoms of ADHD, Study III showed that three different types of inhibitory control – interference control within task, interference control outside task, and prepotent response inhibition – as measured in the preschool period made independent contributions to 2-year longitudinal symptoms of ADHD. Together, the three types of inhibitory control explained approximately 20% of the variance in ADHD symptoms. This result was independent of IQ, social background, as well as co-morbid symptoms of ODD. Our results are consistent with Barkley's view (1997a, b) as well as with previous studies suggesting that impaired inhibitory control is an important factor contributing to early symptoms of ADHD (Berlin & Bohlin; 2002; Sonuga-Barke et al., 2002; 2003; Byrne, DeWolfe, & Bawden, 1998). Importantly, however, the question of independent contribution of different types of inhibitory control to the explained variance of ADHD has not been previously addressed. Thus, the results from Study III take our knowledge of the role of inhibitory control in preschool ADHD one step further by providing unique evidence that deficits in distinct inhibitory functions make significant independent contributions to the explained variance in longitudinal ADHD symptoms. Importantly, these findings suggest different types of inhibitory control to be good predictors of ADHD symptoms over time, at least with regard to shorter time periods. These results could be taken to mean that interference control within task, interference control outside task and prepotent response inhibition may qualify as early neuropsychological risk factors for later developing ADHD.

Although not of direct relevance to the heading of this section, it is appropriate to mention here that relatively few previous studies have addressed the issue of how specifically inhibitory control is related to preschool ADHD by statistically controlling for comorbidity in the analyses. Our findings from

Study III, showing that inhibitory control is a remaining neuropsychological correlate of concurrent and longitudinal ADHD symptoms when controlling for symptoms of ODD, whereas the relations between inhibitory control and ODD disappeared when controlling for symptoms of ADHD, are quite unique. Indeed, studies examining whether executive deficits attributed to ADHD symptoms are related to co-occurring disorders when ADHD symptoms are controlled for, particularly as studied over time, are extremely rare. Thus, Study III extends previous findings in school-aged children, implying that EF deficits in ADHD are not explained by comorbid conditions (Nigg et al., 1998; Nigg, 1999; Willcutt et al., 2005) to the preschool period, at least with regard to inhibitory control.

The results from Study I and III underscore the need for researchers to distinguish between different types of inhibitory processes when studying effects of inhibitory control in ADHD. This is particularly important in relation to the possibility that children with ADHD may show different patterns of competence and deficit for each different inhibitory process as a function of age.

WM in relation to ADHD: Are deficits independent of impaired inhibitory control?

The results from Study IV suggest a significant weakness in verbal and visuo-spatial WM processes in ADHD children of elementary school age. Interestingly, the strongest effect size was found for a verbal task thought to put a heavy load on the executive component of the WM system. This result differs from previous data on WM deficits in ADHD, suggesting deficits to be particularly salient in the spatial domain. One interpretation of this finding is that it is variation in difficulty level or load on the executive component of the WM system, rather than variation in modality (verbal versus visuo-spatial), that is important in demonstrating WM deficits in ADHD.

As previously discussed, recent theoretical models suggest a close interplay between inhibitory and WM processes in controlling behavior, with some sort of common underlying mechanism being shared between these executive components (e.g., Roberts & Pennington, 1996; Engle & Kane, 2004; Kane & Engle, 2002). Although some empirical evidence exists with regard to the nature of the relation between inhibitory control and WM (e.g., Nyberg, Brocki, Tillman, & Bohlin, 2007), further evaluation of this issue is needed. That is, we need to look at whether these two processes are independent, interdependent, or whether one of the inhibitory control and WM components functions as a prerequisite or a superordinate process in relation

to the other (e.g., Barkley, 1997a, b; Hasher & Zacks, 1988; Kane & Engle, 2002). However, extant findings support the notion that WM and inhibition interact to contribute to goal-directed behavior (Kane & Engle, 2002; Hartman & Hasher, 1991; Roberts, Hager, & Heron, 1994; Nyberg, Brocki, Tillman, & Bohlin, 2007). The results from Study I are in line with such data, in that an overlap between certain types of inhibitory control and WM was shown in the dimensional analysis. Together, these findings raise the question of whether observed impairments in inhibitory control and WM represent common or independent aspects of poor EF in children with ADHD. Study IV provides some preliminary, yet intriguing data regarding this issue.

Findings from logistic regression analyses in Study IV showed that deficits in WM contributed with variance over and above that of prepotent response inhibition in predicting group membership (ADHD versus controls). In contrast, prepotent response inhibition contributed with variance that was not independent of WM. These results imply that deficits in WM and prepotent response inhibition represent common variance in relation to ADHD, but also that WM contributes with variance independent of prepotent response inhibition. As with inhibitory control, WM is a broad cognitive construct involving several components. Interpreted in terms of the most influential model of WM (Baddeley, 1992; Baddeley & Hitch, 1994), this cognitive system involves verbal and visuo-spatial storage as well as an executive component that coordinates information from the storage components, processes this information and controls behavior in relation to task demands. Thus, whether deficits in inhibitory control and WM should be viewed as unique or common in predicting ADHD may depend on the particular WM component as well as on the type of inhibitory process under study. The findings from Study IV do not allow us to draw any definite conclusions regarding this issue. However, it is interesting to note that it was only a verbal WM task thought to put a heavy load on the executive WM component that made an independent contribution in the regression analyses. Further, the pattern of inter-correlations between the WM tasks and prepotent response inhibition showed a significant correlation only between a spatial WM task (thought to put a heavy load on spatial storage) and prepotent response inhibition (i.e., the inhibitory conflict task). Although preliminary, these results could be taken to indicate that WM deficits linked to the central executive of the WM system represent variance independent of inhibitory control in children with ADHD, whereas difficulties with storage of information may represent variance common to impaired prepotent response inhibition, at least with regard to children of elementary school age.

With regard to variations in type of inhibitory control in relation to the pattern of shared variance between inhibitory and WM processes, similarity

in findings could be observed in the non-clinical and clinical studies included in the current thesis. To be more precise, the result from Study IV, suggesting shared variance between prepotent response inhibition measured by the inhibitory conflict task and WM, is similar to the factor analytic findings in Study I and the inter-correlational findings in Study III. These results showed common variance between the Stroop-like task and WM and an interference composite (i.e., interference within task) and WM, respectively. Indeed, the type of inhibitory control measured in Study IV is similar to that tapped by the Stroop-like task and the interference-composite, in that these inhibitory variables require the individual not only to stop a prepotent incorrect response, but also to shift to a correct but not prepotent response. Thus, it may be that this type of inhibitory control involves a great deal of WM processes, in that a complex rule needs to be held active in mind to prevent falling prey to the incorrect response. If the type of inhibitory control that merely requires a response to be withheld had been used in Study IV, or yet other forms of inhibition (see Friedman & Miyake, 2004 for an excellent study on types of inhibition related processes) the pattern of relation between inhibitory control and WM in ADHD might have been different.

In general, the results from Study IV tentatively suggest that inhibitory control and WM may be characterized as related but distinct cognitive domains in predicting ADHD symptoms. These results are somewhat compatible with Roberts and Pennington's (1996) proposition that inhibitory control and WM reflect some sort of general and common cognitive mechanism. Commonality underlying EF has also been suggested by Miyake et al. (2000), with "some sort of common inhibitory process" (p. 89), or "the maintenance of goal and context information in WM" (p.88), being suggested as potential candidates. Further, it seems possible that the extent to which inhibitory control and WM contribute with common or independent variance in explaining ADHD symptoms may not only be related to activation of type of inhibitory control and relative load put on particular WM components (storage versus executive processes), but may also be dependent on the maturational level of the sample studied. This idea is somewhat reflected in the findings of Study II, III, and IV, showing different results with regard to inhibitory control and WM in relation to ADHD symptoms, as studied in samples of different age ranges.

Developmental aspects of EF in normal children and in relation to ADHD

As mentioned in the introduction of this thesis, the classical notion of ADHD as a static disorder is now giving way to a new perspective that characterizes ADHD as a developmentally relative deficit, in which the expression of ADHD symptoms undergoes change with age (i.e., the developmental hypothesis; Barkley, 2003). Indeed, symptoms of hyperactivity have predominantly been observed in younger children and shown to decrease with age, whereas symptoms of inattention have been found to be more constant across childhood (Hart et al., 1995). However, the important question of how the neuropsychological manifestation of ADHD may vary with a child's age has almost been totally ignored in extant ADHD research. Such data should constitute an important step toward a more established understanding of the ADHD phenomenon as a developmentally relative deficit. Together, all of the studies included in the present thesis focusing on samples representing different age ranges and variations in severity levels of ADHD symptoms suggest that developmental change is an important factor that should be taken into consideration when searching for neuropsychological ADHD endophenotypes.

When viewing ADHD from a developmental and dimensional perspective, it follows that our understanding of EF in relation to ADHD must, at least in part, derive from data specifying the typical development of executive control. Therefore, Study I investigated the development of EF based on the executive dimensions derived from the factor analysis, described earlier, in a normal sample aged 6 to 13. This means that the developmental data may be taken to represent age effects at the level of executive components, rather than variance idiosyncratic to specific tasks, which should be regarded as strength of this study. In general, the results showed developmental maturation on the inhibition dimension, in which withholding of a response was primarily required, at 10 years of age. In contrast, developmental improvement on the WM dimension continued into adolescence. Thus, it can be concluded that our results are consistent with Barkley's developmental prediction of EF (1997a, b), suggesting that inhibitory control is an early developmental precursor to or a factor that "sets the stage" for more complex EFs such as WM.

The findings from Study II, III, and IV provide further support for Barkley's developmental prediction as studied in relation to ADHD symptoms. In Study II, the effects of age on the relation between EF and symptoms of ADHD in typical children aged 6-13 were investigated. The findings are unique in showing that poor inhibition was most clearly associated with

ADHD symptoms (both hyperactivity and inattention) for younger children, whereas poor functioning with regard to later developing and more complex EFs, such as WM was associated with inattention symptoms for older children.

In Study III, different types of inhibitory control were associated with ADHD symptoms in a preschool sample including children at risk for ADHD and/or ODD. In contrast, no relations were obtained between WM and symptoms of ADHD or ODD, neither concurrently nor longitudinally. This result supports Barkley's (1997a,b) view that ADHD is underpinned by inhibitory deficits in the preschool period. The results from Study III also make an important new contribution to the ADHD research field by providing 2-year longitudinal findings showing that distinct types of inhibitory control may represent separate neuropsychological pathways that give rise to later ADHD symptoms. Although the longitudinal relations between EF and ADHD symptoms were studied only over a two-year period, the results underscore the need for identifying neuropsychological risk factors that can predict later ADHD symptoms as studied longitudinally over extended periods of time.

Study IV showed impaired performance in WM processes and mild impairment in prepotent response inhibition in elementary-school-aged children with a diagnosis of ADHD compared to normal controls. These results are partly inconsistent with the results obtained in Study III, in that the extent to which ADHD symptoms could be accounted for by problems in inhibitory control and WM varied between the two studies. To be more specific, in Study IV, a general weakness in WM was observed in the ADHD group, with particularly marked impairments on a verbal WM task thought to put a heavy load on the executive processes of the WM system. In contrast, the results from Study III showed an important role for inhibitory control rather than WM in explaining preschool ADHD symptoms. The discrepancy in findings between Study III and IV most likely represent relative immaturity versus maturity in WM and inhibitory processes in preschool children compared to school-aged children. It should be mentioned here that one important methodological issue for developmental research examining neuropsychological function in relation to ADHD is to use tasks that are sensitive to a particular executive deficit at each maturational level. If the difficulty level of a certain task is too low or too high, the results will not reflect true deficits. Indeed, this crucial methodological issue was taken into account in both Study III and IV by selecting tasks designed to be developmentally sensitive to preschool versus school-aged children. Together, the results from Study III and IV indicate that inhibitory control plays an important role in the neuropsychological manifestation of ADHD, particularly so in the preschool period. Deficits in WM, however, seem to constitute an important compo-

ment in the neuropsychology of ADHD in the elementary school age period.

Summary and directions for future research

Salient executive dimensions in ADHD

Previous research indicates that the neuropsychological etiology of ADHD is heterogeneous and complex, presumably involving impairment in multiple neurocognitive mechanisms. Empirical evidence exists for deficits in executive control (Barkley, 1997a, b), regulation of arousal/activation (Sergeant et al., 1999), reinforcement processes (Sagvolden et al., 2005), as well as motivational and temperamental factors (Sonuga-Barke et al., 2003; Nigg, 2006). With regard to EF, it is currently hypothesized that ADHD symptoms can be attributed to executive dysfunction in only one particular subgroup of children (Nigg et al., 2005; Nigg, 2006). The combined results of the present thesis show that impairments in inhibitory control and WM contribute significantly to ADHD symptoms as studied in both non-clinical and clinical samples. Thus, these particular EF components should account for a relatively large part of the neuropsychology in the ADHD subgroup or endophenotype characterized by executive dysfunction. Further, the current findings indicate that the extent to which ADHD symptoms can be attributed to deficits in inhibitory control and WM, and whether these components represent common or independent variance in the explanation of ADHD symptoms, may depend on the particular type of inhibitory process under study as well as relative load put on the WM components (storage versus executive processes). Future research should focus on better characterizing the role of specific types of inhibitory and WM processes in the manifestation of ADHD. Further, experimental designs that can isolate the WM components and clarify their relation to different types of inhibitory control should lead to further advances in our understanding of the extent to which WM deficits are independent of difficulties in inhibitory control in children with ADHD.

A developmental perspective on the neuropsychology of ADHD

From a developmental perspective, neuropsychological dysfunction in ADHD should be viewed as interruptions or delays in unfolding developmental pathways, which give rise to this disorder. In my opinion, such a view implies that not only behavioral symptoms, but also neuropsychological function or dysfunction should alter with a child's maturational level. Indeed, our findings from Study II, III, and IV, indicating that deficits in inhibitory control and WM may be of different importance in explaining

ADHD symptoms depending on age, are among the first to show that neuropsychological dysfunction in relation to ADHD varies with maturational level. As Nigg (2006, p. 316) states “Too little is known about how stable the ADHD DSM-IV-TR subtypes are over time (Lahey et al., 2005), much less about how stable a neuropsychological finding in a particular child with ADHD would be over time”. Findings from the present thesis underscore the need for longitudinal investigations that track age-related changes in neuropsychological function as well as in ADHD symptoms, spanning periods from preschool to elementary school age. Indeed, research that tracks age-related changes in executive or other deficits attributed to ADHD should play an important role in the search for neuropsychological ADHD endophenotypes (Castellanos & Tannock, 2002).

The dimensional hypothesis of ADHD

With regard to the dimensional hypothesis of ADHD, available research indicates that ADHD is most likely a dimensional disorder (Levy et al., 1997), representing the extreme of or a delay in normal traits. It follows from this view that performance on tasks that are sensitive to neuropsychological dysfunction should correlate with ADHD symptoms in a linear manner, such that the degree of association should be similar across symptom severity levels. In accordance with the dimensional perspective, the samples in my studies represent a wide range of ADHD symptom severity levels in that normal children (Study II), children identified as being at risk for developing ADHD (Study III), and children with diagnosed ADHD-C (Study IV) have been included. The present studies did not statistically test the dimensional hypothesis of ADHD, as we were not able to compare degree of association between EF and symptom severity level across studies. However, the results showed that inhibitory control and/or WM, depending on the age range of the sample, consistently fell out as significant factors in relation to ADHD symptoms regardless of symptom severity. Further, similarity in the pattern of results with regard to shared variance between inhibitory control and WM was also found across the non-clinical and clinical studies. These findings could be regarded as being compatible with, albeit not proving, the dimensional hypothesis. Future studies should include samples of children representing the whole ADHD symptom spectrum so that the stability of the neuropsychological contribution to ADHD symptom across severity levels can be directly tested. It should be mentioned here that it is possible to obtain non-linear relationships between task performance and ADHD symptoms not because ADHD is not normally distributed in the general population, but because the tasks are insensitive to high or low symptom levels. Therefore, such methodological issues need to be taken into account in future research.

Concluding remarks

In summary, the primary contribution of my studies to our on-going understanding of ADHD is the novel results supporting the view of ADHD as a dimensional and developmental disorder, where distinct executive components and behavioral symptoms are of different importance depending on the child's age. To be more specific, both my non-clinical and clinical studies suggest that inhibitory control and WM are important in predicting ADHD symptoms, with deficits in inhibitory control primarily being associated with ADHD symptoms for preschool and younger school-aged children, and deficits in WM being associated with ADHD symptoms for elementary school aged children. In other words, the message to take home from the present thesis is that age matters not only in the behavioral, but also in the neuropsychological manifestation of ADHD. To our knowledge, these findings are novel and should motivate further investigation into how potential neuropsychological endophenotypes in ADHD vary with age and symptom dimension. Such research should constitute a first step toward modification of diagnostic procedures found in the current DSM-IV-TR criteria, so that diagnostic thresholds and treatments with regard to both behavioral symptoms and neuropsychological deficits can be adjusted to the child's age

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