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Working Memory and Higher-Order Cognition in Children

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ACTA UNIVERSITATIS UPSALIENSIS
UPPSALA
2008

ISSN 1652-9030
ISBN 978-91-554-7274-0
urn:nbn:se:uu:diva-9271

Dissertation presented at Uppsala University to be publicly examined in Sal VIII, Universitetshuset, Uppsala, Monday, October 6, 2008 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract
Tillman, C. 2008. Working Memory and Higher-Order Cognition in Children. Acta Universitatis Upsaliensis. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Social Sciences* 43. 77 pp. Uppsala. ISBN 978-91-554-7274-0.

Higher-order cognitive functions, such as executive function (EF) and intelligence, are crucial to the everyday functioning of human beings. Gaining knowledge about these functions is important for our general understanding of human nature as well as for our ability to help those who may not develop these processes optimally. The present thesis focused particularly on the EF component working memory (WM), described as the ability to maintain informa-tion in consciousness during short time periods with the purpose of using that information in complex cognition. The major aims of the thesis were to increase our understanding of higher-order cognition in children as well as of deficiencies in intelligence found in children with Attention Deficit Hyperactivity Disorder (ADHD). We approached these aims by studying the interrelations among EF-related components in terms of their independent contributions to intellectual functioning. We also studied whether the lower intelligence in children with ADHD was mediated by fundamental EF-related components or whether these deficiencies went beyond the weaknesses in these specific cognitive functions.

Interpreting the present data, we suggest that intellectual functioning in children is best viewed as representing a system of primarily independent parts that may be accompanied by an overarching common mechanism. The multiple components involve, but are surely not limited to, WM functions, inhibitory functions, sustained attention, and processing speed. One of these functions, WM, was found to be further partitioned into domain-specific executive WM processes and domain-specific short-term storage processes, all of which constitute important aspects of higher-order cognitive functioning. We have further learned that deficits in fluid intelligence in children with ADHD may entail more than weaknesses in specific central cognitive functions. This additional deficit is cautiously interpreted as involving supe-rior executive attention functions setting the stage for the development and integration of the EF system as well as the “intelligence system”.

Keywords: Intelligence, executive function (EF), working memory, ADHD, children

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ISSN 1652-9030
ISBN 978-91-554-7274-0
urn:nbn:se:uu:diva-9271 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-9271)

List of Papers

The present thesis is based on the following three studies, which will be referred to in the text by their Roman numerals.

I Tillman, C. M., Bohlin, G., Sørensen, L., & Lundervold, A. J. (2007). *Working memory components, interference control, sustained attention, and processing speed as independent predictors of intelligence in children*. Manuscript under revision for publication.

II Tillman, C. M., Nyberg, L., & Bohlin, G. (2008). Working memory components and intelligence in children. *Intelligence, 36*, 394-402.

III Tillman, C. M., Bohlin, G., Sørensen, L., & Lundervold, A. J. (2008). *Intellectual deficits in children with ADHD beyond central executive and non-executive functions.* Manuscript under revision for publication.

Contents

Introduction

The practical importance of human mental abilities is evident to all people. Everyday tasks, such as reading a newspaper, taking directions, or calculating the amount of tip to leave at a restaurant all require relatively complex cognitive action. The scientific relevance of the extreme complexity of human higher-order cognition, however, rather lies in what information it can give us about the thinking and functioning of human kind, in general, and of individuals, in particular. In other words, the complexity of human thinking can be viewed as a factor that separates us and other animals, and therefore, conceptions of human mental ability have far-reaching implications for theories of human nature. Historically, the modern study of individual differences in cognitive ability arose, at the end of the 19^{th} century, from the need for a tool with which to identify children with special educational needs. Alfred Binet discovered that, together, a series of small readily measured tasks consistently distinguished between those children who had cognitive problems and those who did not. The important implications of this early finding were that individual differences in general cognitive ability were operationalizable and, first and foremost, that performance appeared to predict functioning in real life.

Since this early conceptualization of IQ, the study of individual differences in cognitive ability has developed greatly, and at present there is a major focus on higher-order functions such as executive function (EF) and different types of intellectual abilities. EF is a broad and general construct that refers to the cognitive functions needed for the deliberate control of thought, emotion, and ultimately action (i.e., goal-directed behavior; e.g., Miyake et al., 2000; Welsh & Pennington, 1988). The increased interest in EF during the past decade is partly a result of findings indicating that individual differences in these functions are linked to many different kinds of neuropsychiatric behavior problems. The focus of clinical EF research has been on the developmentally related disorder attention deficit hyperactivity disorder (ADHD), which highlights the particular relevance of studying EF in children.

Although more recent conceptualizations of intelligence are still insufficient in some regards, clearer definitions have indeed emerged since the time of Binet. Several of these definitions bear a clear resemblance to the general definition of EF (e.g., Sternberg, 1985). Also, both EF and intelligence have been primarily linked to the same areas of the brain, that is, the prefrontal cortex. There is thus only a short step from studying EF to studying intelligence. In summary, studying the interrelations of different aspects of higher-order cognition (i.e., EF and intelligence) as well as how these functions may break down in some psychiatric conditions appears to be an effective means of enhancing our understanding of all of these aspects of higher-order cognition, in the end enabling us to learn more about human behavior in general. The study of children is particularly important, because knowledge about the young is very limited regarding these issues. Moreover, given the dramatic developmental changes that occur, it cannot be simply assumed that adult theories and empirical findings are directly applicable to the functioning of children.

Theoretical Propositions About Intelligence

At the beginning of the 20th century, Spearman (1927) noted that all the tests that made up batteries, such as that proposed by Binet, tended to correlate with each other. He interpreted this as indicating that they all drew upon a single component, which he referred to as *g*. In his view, the common variance of a given universe of cognitive tasks, or *g,* was what differentiated people with high mental ability, or intelligence, from those with low ability.

When it was found that the general factor did not account for all of the variance in test results, the notion of specific factors began to arise. Thurstone (1938) proceeded from this multicomponential view and assumed that human intellectual abilities were better resolved into a small number of independent factors.

Detterman (e.g., 1982, 2000) is a more recent proponent of the multifactorial view of intelligence. He has indeed acknowledged the importance of *g*, recognizing that it is what carries the explanatory weight in individual differences in ability. Further, it predicts more and is implicated in a wider range of behavior than any other psychological construct. Unfortunately, however, we do not know what *g* is, so this well-documented importance actually falls short of real relevance (Detterman, 2000). It has even been suggested that *g* is altogether the wrong thing to study, because it is a higher-order characteristic of a complex system. It must also be kept in mind that *g* is only a statistical concept, which indicates that mental tests are all positively correlated. It does not explain why this correlation occurs. Viewed from a bottom-up perspective, we need to achieve a good empirical description of the primary parts of the system before we can attempt to explain the higher-order concepts (Detterman, 1982). To specify Detterman's theoretical propositions, he has argued that *g* is made up of a set of independent cognitive abilities tied together into a well-integrated system, rather than representing a single underlying entity.

Detterman (2000) has based his view on, among other factors, a) difficulties in exceeding small to moderate correlations (around .30) between different cognitive tasks, b) findings showing that a set of cognitive tasks predict intelligence as well as intelligence tests predict each other, and c) results showing that even though basic cognitive tasks can be combined to predict *g*, they themselves do not show a large general factor. Therefore, basic cognitive tasks do not serve as proxies for *g*. Instead, each appears to provide its own independent contribution to *g*.

The behavioral definition of general intelligence was defined early on as judgment, otherwise called good sense, initiative, and the ability to adapt oneself to circumstances (Binet & Simon, 1916). Wechsler (1944) held that intellectual behavior concerns the global ability of an individual to act with purpose, to think rationally, and to deal effectively with his or her environment (Wechsler, 1944). A more recent definition was presented by Sternberg (1985), who defined human intelligence as mental activity directed toward purposive adaptation to, and selection and shaping of, real-world environments relevant to one's life.

One division in the concept of intelligence that has been widely adopted is that between fluid and crystallized intelligence, which was proposed by Cattell (1963). Fluid intelligence is related to the solving of abstract reasoning problems and refers to the potential to adapt to new situations and form new ideas, which in turn depends on the ability to perceive relations and correlations. Crystallized intelligence, on the other hand, is composed of information that is acquired, partly through fluid intelligence, via education, experience, and socialization. Based on clinical neuropsychological behavioral data as well as on neuroimaging data from normal subjects, it has been suggested that fluid intelligence is particularly linked to the integrity, structure, and function of the lateral prefrontal cortex (Gray & Thompson, 2004; Shaw, 2007), thus showing a clear similarity to EF with regard to neural bases. Crystallized intelligence may instead be localized to more parietal and posterior regions of the brain (Gray & Thompson, 2004).

What are Executive Functions?

Executive functions (EF) could perhaps be viewed as the quintessence of higher-order cognition. These functions are scientifically captivating because of their complexity. Unfortunately, there are no uniform, agreed-upon definitions of EF in the literature, even after decades of extensive research, which probably reflects their intricacy. However, the majority of experts on this topic concur that EF is related to higher-order control processes involved in the regulation of goal-directed thought and action (e.g., Baddeley, 2007; Barkley, 1997; Miyake et al., 2000; Welsh & Pennington, 1988). Although EF involves links between different parts of the brain (e.g., Andrés, 2003), these processes have been primarily linked to the prefrontal, cortical areas of the brain. One of the foremost cognitive frameworks associated with the study of EF is the working memory (WM) model proposed by Baddeley (e.g., 2007). This model will be described later on in the thesis. In line with the broad definitions of EF, this term was long used to describe a unitary control function, with the resulting use of very global and complex tasks to assess this function. The prefrontal cortex is, however, a multifaceted area of the brain, and in more recent years, the evidence for regional specialization within the prefrontal cortex for different EF components has accumulated (e.g., Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Shallice et al., 1994). Brain areas outside the prefrontal cortex have also been found to be differentially linked to separate EF components (e.g., Andrés, 2003).

These arguments speak for a shift away from a totally unitary view of EF and toward an integrative perspective that incorporates unitary and componential views. Consequently, experts in this area of research have tried to break down the broader concept of EF and rather define a few core functions that could be considered to lie at the heart of active control of goal-directed thought and action. Based on prior theoretical assumptions and empirical data, Miyake and colleagues have more closely studied the three functions inhibition of inappropriate habitual responses (i.e., prepotent response inhibition), mental set-shifting, and updating of working memory (WM), and have indeed found support for the separability of these functions as well as their specialized importance in different complex EF tasks (Miyake et al., 2000). Further, their work provides convincing support for the notion of *the unity and diversity of EF*, implying that these executive subfunctions certainly are separable, although they also show commonality (Friedman, et al., in press; Friedman et al., 2006; Miyake et al., 2000). This evidenced commonality is particularly interesting in that it suggests a hierarchical view of EF. The basis of the commonality has been interpreted by Miyake et al. (2000) as an executive attention system (see e.g., Baddeley, 2007; Engle & Kane, 2004), which is important to all EF components.

Developmental models are at large in agreement with the EF model presented by Miyake and colleagues. Diamond has proposed a developmental model that emphasizes the separation of important EF components in children (2006). Support for the independence of EF components in children is demonstrated in separate developmental trajectories (e.g., Carlson, 2005; Diamond, 2001, 2002), and in that the performance of young children is influenced more by inhibitory demands than by WM demands (Davidson, Amso, Anderson, & Diamond, 2006). Garon, Bryson, and Smith (2008) used an integrative model, based on Miyake and colleagues' EF theory (2000), to analyze the existing developmental EF literature and their findings were generally in keeping with Diamond's model. The view that was advocated by their analysis suggests that EF components are relatively independent in children, becoming increasingly integrated during childhood.

The clinical relevance of EF is largely supported by the strong link found to behavior problems characteristic of ADHD, that is, inattention, impulsivity, and hyperactivity. A general agreement today is that ADHD most likely is related to multiple etiological factors, whereby deficits in EF presumably constitute one (Banaschewski et al., 2005; Castellanos & Tannock, 2002; also see, Barkley, 2006, for a review). Associations between ADHD and deficits in inhibitory control constitute the most robust findings (Nigg, 2001; Willcutt et al., 2003), but impairment in other EF components has also been implicated in the disorder (e.g., WM and sustained attention; Barkley, 1997; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rapport et al., 2008).

Executive Functions and Intelligence

EF is strongly implicated in several views of intelligence. For example, Campione, Brown, and Ferrera (1982) considered EF to be "central to notions of intelligence", and Butterfield and Belmont (1977) suggest that EF is "close to what is meant by intelligence". Sternberg (1985) has even proposed that the *g* factor should be seen as a reflection of the fact that EF is common to all cognitive tests. Although the notion of equivalence between EF and intelligence has received massive criticism in more recent years (e.g., Barkley, 1997; Blair, 2006; Crinella & Yu, 2000; Friedman et al., 2006), there is no doubt about the existence of a strong link between these two concepts. However, it must be remembered that the study of intellectual ability emanates from the traditions of differential psychology and psychometrics, whereas the concept of EF stems from clinical neuropsychology. The terms clearly overlap theoretically, but because they have mainly been studied within these separate research fields, less is known about *how* they are related. During more recent years, however, this type of research has increasingly emerged.

Even if complex EF tasks, derived from a unitary view of EF, have been inconsistently related to intelligence (see e.g., Ardila, Pineda, & Rosselli, 2000; Arffa, 2007; Donders & Kirsch, 1991; Welsh, Pennington, & Grossier, 1991), an extensive link of this kind is evidenced in both children and adults when more well-defined tasks of WM and inhibitory functions are adopted, as we will see later on (e.g., Dempster, 1991; Engle & Kane, 2004; Jarvis & Gathercole, 2003; Pascual-Leone, 1987).

It should be mentioned that not all EF components, derived from a non-unitary view of EF, may be equally relevant to intelligence. In a study on young adults, Friedman et al. (2006) demonstrated that in bivariate relations, prepotent inhibition and mental set-shifting were related only to crystallized intelligence and not fluid intelligence, whereas updating of WM was related to both types of intelligence. Given the relatedness of separate EF components, it is also important to ask questions such as: What is the independent contribution of this particular function to explaining intelligent behavior, after accounting for the explanatory power of other related EF components? The Friedman et al. study is one of few asking this kind of question. They found that when controlling for the other two EF components, neither prepotent inhibition nor mental set-shifting predicted intelligence, whereas updating of WM did. Their conclusions were strong in suggesting that not all EF components are related to intelligence, and further that WM-related functions are among the more central functions in intelligence.

Working Memory as Higher-Order Cognitive Functioning

The ability to mentally maintain goal-relevant information for a short period of time in an active state, while simultaneously manipulating that information or processing new information, has been considered one of the most significant achievements of human mental evolution (Goldman-Rakic, 1992). This ability makes planning, reasoning, problem solving, reading, and abstraction possible. Researchers refer to the term "working memory" to describe the processes responsible for short-term maintenance and processing of information. As indicated in the section on EF, WM processes are highly relevant to the concept of EF. In a broad context, WM has been described as a temporary storage system that underpins the human capacity for coherent thought and action (Baddeley, 2007). In other words, WM is more than memory. Rather, it is memory *at work*, in the service of complex cognition. This crucial functional aspect of immediate memory has resulted in WM-related functions being put at the core of complex cognition according to leading WM theories (Baddeley, 2007; Engle & Kane, 2004), and thus WM has become a central construct in cognitive psychology. Given these definitional assumptions about WM, it is easy to see the relevance of studying the relation between WM functions and the ultimate concept of complex cognition – intelligence.

It is also interesting to note that although extensive definitions of WM exist and although researchers within this area have agreed upon some common features of such a system, the nature of the underlying processes responsible for WM still stirs up debate among cognitive theorists. Likewise, definitions of intelligent behavior are fairly well agreed upon, but the characteristics of the cognitive processes involved in this type of complex cognition are highly disputed. Thus, it is noteworthy that with regard to both of these concepts of higher-order cognitive functioning there is a need for more in-depth description of their underpinnings. It is our belief (as well as others') that we can enhance our understanding of both WM and intelligence by studying how they are related. I will return to how the relation between WM and intelligence has been studied and what is presently known about this relation in a later section of the introduction. But first, let us consider some important theoretical assumptions about WM.

Theories of Working Memory

Most WM theories of today originate, in one way or another, from the early version of the multicomponent model of WM proposed by Baddeley and Hitch (1974). At the time, Baddeley and Hitch acknowledged that although a considerable amount of important research had been conducted to address fundamental questions about immediate memory itself, such as how information is encoded and why we forget, knowledge was basically lacking regarding the role of immediate memory in more complex cognitive behavior. Baddeley and Hitch's multicomponent model was developed as a response to their data, which could not be explained by any existing unitary temporary storage model. Their data showed that decreasing the capacity of the system that underpins retention of digits by repeating series of numbers aloud impaired complex cognitive functioning, such as reasoning. In other words, the capacity of an immediate memory store appeared to clearly limit more complex cognitive functioning. Based on these and other similar data, Baddeley and Hitch decided to replace the former popular notion of a unitary short-term memory with a multicomponent system including two separate domain-specific storage components (verbal and visuospatial), in addition to the domain-general control mechanism, the central executive. To point out the important emphasis on the functional role of the proposed system in complex cognition, the term *working* memory was chosen. Further, this initial model of WM was also based on the evolutionary idea that it was unlikely that immediate memory had developed for the sole purpose of allowing an organism to store or rehearse information while doing nothing else. Instead, an adaptive immediate memory system would allow the organism to keep task-relevant information active and accessible *during* the execution of complex cognitive and behavioral tasks. As mentioned above, this model is a common framework adopted in the study of EF, given the overarching executive nature of the central executive of the WM system.

The two storage components of the multicomponent model are involved in temporarily maintaining verbal and visuospatial information, respectively, active via rehearsal mechanisms. The majority of the research on the multicomponent model has been dedicated to these storage components, as they are more tractable than the central executive. This has left the central executive, which according to Baddeley is the most important component, least understood. The term was long used as a ragbag of all conceivable supervisory processes and unanswered questions about the control of cognitive processes. However, in line with the *diversity* notion of EF, Baddeley (1996, 2007) has recently attempted to fractionate the responsibilities of the central executive into distinguishable attention functions, particularly associated with the prefrontal cortex and the dorsolateral frontal cortex (Fletcher & Henson, 2001). However, he does not seem to argue against the EF components proposed by Miyake et al. (2000), as constituting relevant aspects of the central executive (see, Baddeley, 2007, p. 203). In other words, although the specification of Baddeley's central executive has achieved some success, its subfunctions are still vaguely defined. During recent revisions of the model, a fourth component has been added to the system – the episodic buffer, which has been implicated in the link between WM and long-term memory (LTM) and in the interaction between the two storage components (Baddeley, 2000, 2007). Baddeley's multicomponent model has received support by evidence from studies of children (Alloway, Gathercole, Willis, & Adams, 2004), adults (see, Baddeley, 1996; Jonides, Lacey, & Nee, 2005, for reviews), and neuropsychological patients (Vallar & Papagno, 2003).

The short-term storage components are typically assessed using simple span tasks, requiring the temporary storage of a sequence of items (e.g., digits, words, or locations) for immediate recall. Measurement of the central executive, however, has stirred up more debate in the literature – an issue that could probably be traced back to an insufficient understanding of these processes. Based on Baddeley's theoretically formulated assumptions concerning the functional role of WM as well as the evolutionary notion of such a system, Baddeley defined early on the performance of two concurrent tasks (i.e., dual-tasks) as tapping aspects of the central executive. However, what opened up WM research to the study of individual differences was the development of a task that, based on the proposal that WM involved both storage and processing of information, combined these two functions. This task became known as the complex WM span task (Daneman & Carpenter, 1980). Tasks within this paradigm have been widely adopted in the study of WM. However, more recent task developments have also emphasized the processing or manipulation of the to-be-remembered information itself, rather than processing of information in a second task. Such tasks involve, for example, reordering the stored items (e.g., in a backward order, in the order of size, or in alphabetic order) before reciting them. The debate is still open as to whether these different types of WM tasks assess the same kind of processes (Conway et al., 2005).

Influenced by Baddeley and Hitch's multicomponent model, Engle and Kane (2004) defined WM capacity as the ability to apply activation to memory representations, to either bring them into focus or maintain them in focus, particularly in the face of distraction. This definition identifies a key point in their WM model – the inhibitory function, interference control. According to the WM theory of Engle and Kane, when being exposed to interference while performing a cognitively demanding task, one needs to block this interference out of mind to be able to perform the task successfully. This distractor blocking ability goes hand in hand with another key concept in their theory, that is, executive attention. The ability of executive attention to combat interference has been suggested to lie at the heart of individual differences in WM capacity. In contrast to developmental models (e.g., Diamond, 2006), this theory thus means that inhibitory interference control is an intrinsic aspect of WM in adults. The role of executive attention in a broader context of general cognitive control is described by Engle and Kane as twofold, with *active maintenance of task goals* being one factor and *resolution of response competition or conflict* being the other. Although a thorough comparison of the Engle and Kane theory and Baddeley's model is beyond the scope of the present thesis, it could briefly be said that the structures of their proposed WM systems show clear similarities, with separate short-term stores for verbal and visuospatial information and a domain-general executive WM component.

In accordance with these theories, in the present thesis the term WM is used when referring to the whole WM system, including both storage and executive components. The label short-term storage or short-term memory (STM) is used when referring to the storage components of the WM system, and the term executive WM processes/components is used when referring to executive control processes of the WM system.

The "Executive Family"

I have now separately discussed three terms involving "executives" – the central executive (Baddeley, 2007), executive attention (Engle & Kane, 2004), and EF. One might ask how the ideas about these executives are related to each other, on a conceptual level. It should first be noted that this issue has not been discussed in a direct manner in the literature. I will here try to present a conceptual account sufficient for the reader to follow the arguments in the thesis.

The proposed central executive in Baddeley's WM model is frequently equated with the concept of EF, in that it is considered a general control function that regulates other cognitive processes. The notion of unity and diversity of EF, advocated by Miyake et al. (2000), thus describes an idea where the central executive (or the umbrella term EF) is fractionated into separate EF components (e.g., inhibition, updating of WM, and mental set-shifting), all of which also appear to draw on some common resource. It has been suggested that this mechanism, which is important to all EF components, is a superior control function responsible for keeping task-relevant information active in WM during controlled processing, supposedly through executive attention functions tied to the dorsolateral prefrontal cortex (see e.g., Baddeley, 2007; Engle & Kane, 2004; Kane & Engle, 2002). From a developmental point of view, executive attentional processes have also been put in a broader perspective, wherein they are proposed to have the function of integrating the separate executive subfunctions so they can work together in a coherent and complex EF system (Garon et al., 2008).

This brief and somewhat simplified outline of the "executive relatives" can also be used to summarize how Baddeley's central executive is currently described. In spite of its "boss-like" title, the central executive does not appear to be depicted as an executive of the executive functions. It rather appears to be used as a theoretical collective term for a given universe of EF components. In addition to involving separate EF components, such as inhibition, updating, and mental set-shifting, executive attentional functions that are tapped by all separate EF components may be implied in the concept of the central executive. The central executive (or the term EF) is thus multi-componential, and different WM tasks as well as other EF tasks (e.g., inhibition tasks) tap different aspects of these multiple functions. Hereafter, I will use the specific terms for the EF components (such as *inhibition*) to refer to these specified aspects of the central executive (or EF), whereas the term *executive attention* will be selectively used for the theoretical construct that is tapped by all EF components to different degrees, with perhaps WM being its closest ally. However, executive attention is described as such a broad construct – involving complex attentional processes that integrate different EF components so that they work as a system – that it is unlikely the relatively simple tasks used to assess WM can completely capture the executive attention construct. The term *executive WM processes/components* will be used when referring to the putative aspects of executive attention tapped by WM tasks – in other words, those aspects that are responsible for maintaining information active while engaging in cognitive processing.

It must be said again that all executive terms are still very vaguely understood in the literature, which has resulted in some conceptual confusion. Therefore, I do not think every researcher in all fields dealing with EF constructs would agree with this description. It is, however, a theoretically sound model of "the executives", and I have adopted it for the purposes of this thesis (see Figure 1).

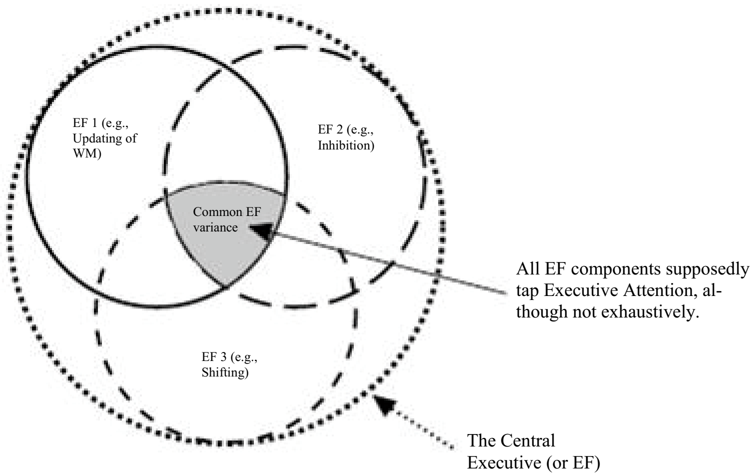

Figure 1. The adopted executive framework for the purposes of the present thesis, based on an integrative view of executive functioning (EF) (e.g., Miyake et al., 2000)

How are Working Memory and Intelligence Related?

There is no doubt that WM is one of the most strongly evidenced cognitive functions in intelligence in both children and adults (see e.g., Oberauer, Schulze, Wilhelm, & Süss, 2005, for a meta-analysis; Jarvis & Gathercole, 2003; Pickering & Gathercole, 2004). The research conducted by Engle, Kane, and colleagues has been largely driven by the central question of *why* WM measures so successfully predict performance across a range of complex cognitive abilities, such as intelligence, reading comprehension, and mathematical ability. The answer to this question would have clear ramifications for general WM theory. Although it has previously been argued that WM and intelligence reflect the same underlying processes (e.g., Kyllonen & Cristall, 1990; also see, Engle et al., 1999), most researchers have now moved away from the notion of their equivalence (e.g., Conway, Kane, & Engle, 2003; Blair, 2006). There is, however, still a debate as to how strong the relation between WM and intelligence really is (Ackerman, Beier, & Boyle, 2005; Beier & Ackerman, 2005; Kane, Hambrick, & Conway, 2005;

Oberauer et al., 2005). Regardless of how this relation is viewed, it is essential, in this research, to be able to empirically distinguish between the main WM components, that is, storage and executive components. As mentioned above, given that the storage components serve simply to store information, measurement is relatively straightforward. However, given that WM tasks tap into the whole WM system, assessing the executive WM processes isolated from the storage components is more complicated. There is, however, a theoretically based solution to this problem. Given that a WM measure, according to Engle and Kane's theory, assesses both short-term storage and executive WM processes, whereas a STM measure assesses mainly short-term storage, it could be argued that by removing the variance in WM tasks that is shared with STM tasks, executive WM processes would be left in the residual WM performance.

Engle and Kane make a strong theoretical argument suggesting that the executive WM component is the core of WM and that it is what drives the relation to intelligence. However, it could be argued that the value of their empirical evidence for this idea may be limited because they have not used a valid operationalization of the *separate* WM components according to their own theory (e.g., Engle et al., 1999; Kane et al., 2004). Empirical data on the issue of the relative importance of the WM components are generally scant due to similar concerns. Our knowledge is thus fairly limited regarding the role of the WM components in intelligence, and this is especially true in children. In adults, the work by Colom and colleagues comprises a majority of the studies that have adequately assessed the short-term storage component using STM tasks, and the executive WM component with the leftover variance in WM tasks after removing the variance shared with STM. Their accumulated findings (e.g., Colom, Abad, Rebollo, & Chun Shih, 2005; Colom, Flores-Mendoza, Quiroga, & Privado, 2005) give short-term storage processes a greater role in intelligence, as compared to Engle and Kane. In summary, there is a dispute in the literature, first, as to how the WM components should be operationalized and, second, as to the relative weight of the separate WM components in relation to intelligence.

Working Memory in Children

In the view of neo-Piagetians, such as Pascual-Leone (e.g., 1987), WM is considered to place constraints on and act as a limit of the general cognitive functioning of a child – an increase in WM capacity results in a possibility to reach a higher cognitive level. In other words, growth in WM capacity is viewed as one of the causal factors of intellectual development in children. In line with this perspective, empirical developmental work has shown that age-related improvement in WM mediates the developmental increases in intelligence during childhood (Case, 1985; de Ribaupierre & Lecerf, 2006; Fry & Hale, 1996, 2000; Pascual-Leone, 1987).

Although there is little doubt about the relevance of WM in intelligence in developmental research, very few studies have investigated the relative importance of the different WM components, which is as imperative in children as in adults. The few studies that do exist, and that have included all three constructs of STM, WM, and intelligence, suggest that both STM and WM performance may be relevant in relation to intelligence (Bayliss, Jarrold, Baddeley, & Gunn, 2005; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; de Jonge & de Jong, 1996; Hutton & Towse, 2001). However, these interpretations are tentative as WM performance partitioned into separate storage and executive WM processes has rarely been studied.

Working Memory…and What Else?

As described above, it appears that WM functions are strongly implicated in intellectual abilities. However, most researchers today agree that this relation is not perfect. Below, I describe some other functions, presented in the literature, that have been suggested to be important to intelligence.

Inhibition

The ability to withhold inappropriate responses or disregard distracting stimuli is referred to in the literature as inhibitory control. A primary role for inhibitory functions in the development of higher-order self-control is highlighted by Barkley's suggestion that this EF sits on top of the hierarchy of EF and sets the stage for the successful functioning of the other functions (1997). Although not all agree that inhibitory functions should be viewed as *the primary* EF, there is a general consensus in the literature that this function, together with WM, constitute the more important ones (Friedman & Miyake, 2004; Miyake et al., 2000; Roberts & Pennington, 1996). The relation between inhibitory functions and WM is one of the more challenging issues in the EF literature. Intense discussion has been sparked by the issue of whether these two central EF components are best viewed as intertwined or separate phenomena. While there seems to be some consensus in the developmental literature of inhibition and WM being relatively independent EF components in children (e.g., Diamond, 2006; Garon et al., 2008), extant views on this relation in adults are more contradictory. I have in previous sections of the present thesis presented examples of these inconsistencies. In Miyake et al.'s EF model (2000) WM and inhibition are viewed as separable EF components, whereas in the theory proposed by Engle and Kane (2004) inhibitory interference control is considered an inherent aspect of WM capacity.

Inhibition does not appear to be a unitary function. It rather seems to be composed of several independent inhibitory-related functions (Barkley, 1997; Friedman & Miyake, 2004). The ability to disregard distracting stimuli, which is referred to as interference control, is the function that has been more specifically implicated in intelligence (Dempster, 1991). Dempster has maintained that it is self-evident that intelligent behavior relies both on the ability to activate task relevant information and on the ability to suppress task-irrelevant information. Thus, overlooking inhibitory processes means overlooking a logically necessary component of intelligence. This holds for both children and adults. Dempster continues by arguing that inhibitory processes are a neglected dimension in the study of intelligence, and that this construct undeniably can make a valuable contribution to leading theories of intelligence. It was concluded that "intelligence cannot be understood without reference to inhibitory processes" (Dempster, 1991, p. 157). From a developmental point of view, Pascual-Leone (e.g., 1987) has also argued for the importance and interplay of several cognitive mechanisms, including an inhibition mechanism, in the development of intelligence.

Sustained Attention

Sustained attention is defined as "the capacity to maintain an attentional focus – a vigilant attitude – for an appreciable interval of time" (Mirsky & Duncan, 2001, p. 21). This definition implies that operationalizations of sustained attention should include *change* in performance across the time course of a task (see, Nigg, 2006; van der Meere & Sergeant, 1988). In other words, the concept of sustained attention differs from processes such as WM, inhibitory functions, and processing speed in that it involves change in performance over time rather than level of the performance as such. Further, an important note to make is that sustained attention is conceptually distinct from WM and inhibitory functions. Nonetheless, empirically, almost any task that spans over an extended time period, regardless of content, will to some extent tax the sustained attention system.

The more explicit relation between sustained attention and intelligence has often been explored less than satisfactorily, which by and large has left our understanding of this link limited. According to Mirsky and Duncan's definition (2001), measures of sustained attention should not include any explicit complex demands. This line of reasoning, however, has rarely been followed in the intelligence literature, where substantial demands on WM and inhibition are frequent (e.g., Schweizer & Moosbrugger, 2004). In combination with the fact that these tasks also do not assess decrements in performance over time, interpretation of performance in terms of sustained attention is difficult. What is even more risky in these cases is to interpret the contribution of WM and inhibitory tasks, independent of sustained attention performance, when sustained attention is measured using such a contaminated task. In summary, knowledge about the function of sustained attention, as measured by theoretically sound tasks, in intellectual behavior is scant, particularly in children, and more research is clearly needed.

Processing Speed

General speed of information processing is one of the more basic cognitive functions, which is not regarded as executive, but still has been strongly and consistently implicated in the higher-order concepts of WM and intelligence (e.g., Fry & Hale, 2000; Jensen, 1987; Kail & Salthouse, 1994). Processing speed has been implicated in higher-order cognition through the idea that people with slower processing speed complete fewer mental operations per unit time. This leads to a failure in carrying out critical operations, a greater likelihood of losing the products of processing through decay, or a reduced ability to keep multiple processing streams active via rehearsal (Kane, Conway, Hambrick, & Engle, 2007).

From a developmental perspective, processing speed is particularly important, in that it has been suggested to account for more variation in the *development* of WM in children than it does in variation among healthy young adults (de Ribaupierre, 2001; de Ribaupierre & Lecerf, 2006; Fry & Hale, 2000; Hale, Myerson, Emery, Lawrence, & DuFault, 2007; Kane et al., 2007). The developmental relations between processing speed, WM, and intelligence is highlighted in the "developmental cascade model" proposed by Fry and Hale (1996). In this model, age related improvement in processing speed is related to an increase in WM capacity, which in turn is related to intellectual improvement (Fry & Hale, 1996). Given the basic nature of this function together with its close relation to WM, intelligence as well as other higher-order cognitive functions, it is important to be able to show whether or not relations between these variables are accounted for by processing speed. As a consequence, processing speed is often included as a control variable in studies investigating contributions to intelligence.

ADHD and Intelligence

ADHD is delineated by a symptom complex, the cardinal features of which include inattention, hyperactivity, and impulsivity. This disorder is one of the most common psychiatric disorders during childhood, with a prevalence of around 3-5% (American Psychiatric Association [APA], 2000; Brown et al., 2001; Kadesjö & Gillberg, 1998). A large majority of children diagnosed with this disorder also have co-occurring behavior problems, such as conduct problems, anxiety, and learning disabilities (Biederman, 2005). Although the specific etiology behind ADHD still is unclear, there is currently general agreement that the causes are heterogeneous (e.g., Castellanos & Tannock, 2002). Etiological factors include variations in genes and environment and, maybe more important, interactions between different genes, and between genes and environment (Castellanos & Tannock, 2002). Although not conclusive, evidence suggests that neurochemical abnormalities are related to ADHD, primarily in terms of the dopaminergic and norepinephrinergic systems (Barkley, 2006). Although major risk genes remain to be identified, genetic studies have provided evidence that it is mainly genes that influence the functioning of the dopaminergic system that appear to be involved in ADHD (reviewed in Stevenson et al., 2005). In accordance with today's view that the etiology is heterogeneous, several different neuropsychological developmental pathways have been suggested for the disorder, involving deficits in EF (e.g., Barkley, 1997), deficient regulation of arousal/activation (Sergeant, Oosterlaan, & van der Meere, 1999), or aversion to delays (Dalen, Sonuga-Barke, Hall, & Remington, 2004; Sonuga-Barke, Taylor, Sembi, & Smith, 1992).

Thus, cognitive impairments, in particular EF deficits, are now recognized as one of the primary components of the complex neuropsychology of ADHD. However, there are indications that the cognitive weaknesses extend to affecting general intellectual ability as well, and it is as highly relevant, as it is controversial to ask what, if anything, such deficits can reveal about the cognitive nature of ADHD.

Controlling or Not Controlling for Intelligence?

In the ADHD literature today, the concept of intelligence is most often involved as a control variable when examining possible etiological factors, such as EF deficits. There is a discussion regarding this control procedure in the literature, where some argue that controlling for intelligence is necessary if conclusions about specific cognitive deficits are to be drawn (e.g., Lahey et al., 1998), whereas others make the point that statistical control for intelligence will obscure, not clarify, matters when examining potential etiological factors underlying ADHD (Barkley, 1997; Nigg, 2006).

This discussion, however, does not seem to go very deep, and the prevailing view appears to be that, as long as we do not know the role of intellectual weakness in these children and as long as we do not know how intelligence is related to etiological factors, such as EF deficits, we might as well present our results both with and without controlling for intelligence (see e.g., Barkley, 1997). In other words, we have solved the problem by letting the reader decide which case is more valid. Yet the problem is that this procedure seems to be carried out by authors, editors, as well as reviewers in a routine manner, without much thought as to the meaning of potential differences, or indeed similarities, in results when controlling for intelligence. The obvious risk of such a procedure is that it prevents us from acknowledging the fact that we truly need more information about the role of intellectual deficits in children with ADHD if we are to gain a comprehensive understanding of the disorder (see, Nigg, 2006, p. 314, for a brief discussion of this point).

ADHD and Intellectual Deficits – What We Know

Although the literature on intellectual deficits in children with ADHD is characterized by some inconsistencies, the general consensus derived from both clinical and non-clinical studies is that ADHD is associated with lower intelligence (Barkley, 1997; Barkley, 1990; Barkley, DuPaul, & McMurray, 1990; Barkley, Karlsson, & Pollard, 1985; Goldstein, 1987; Halverson & Waldrop, 1976; Hinshaw, Morrison, Carte, & Cornsweet, 1987; Kuntsi et al., 2004; Mariani & Barkley, 1997; McGee, Williams, & Feehan, 1992; McGee, Williams, Moffitt, & Anderson, 1989; McGee, Williams, & Siva, 1984; Mill et al., 2006; Moffitt, 1990; Sonuga-Barke, Lamparelli, Stevenson, Thompsom, & Henry, 1994; Sonuga-Barke et al., 2008; Stewart, Pitts, Craig, & Dieruf, 1966; Werry, Elkind, & Reeves, 1987). For example, a twin study demonstrated an association between ADHD and lower IQ, and showed that this association could mainly be accounted for by shared genetic influences (Kuntsi et al., 2004). Differences in intellectual ability have also been found between hyperactive boys and their normal siblings (Halperin & Gittelman, 1982; Tarver-Behring, Barkley, Karlsson, 1985; Welner, Welner, Stewart, Palkes, & Wish, 1977). Further, in a recent meta-analysis, the results were interpreted as indicating that children and adolescents with this disorder have as large (or even larger) deficits in intelligence as those found for EF (Frazier, Demaree, & Youngstrom, 2004). The authors concluded that deficient intelligence should be seen as a "feature of the disorder" (p. 552). Although the authors have clearly shown that intelligence in the case of ADHD is worth taking a closer look at, it is unclear what they mean by a *feature of the disorder*. It should also be mentioned that, similarly to what has been shown for EF abilities, there appears to be clear individual variation in intellectual ability among children and adults with ADHD. In other words, although the average intellectual level of these individuals is lower than that of controls, not all individuals with this disorder necessarily have poorer intelligence.

The strong association that has been evidenced between ADHD and intellectual deficits (e.g., Frazier et al., 2004; Kuntsi et al., 2004) should perhaps prompt us to start thinking about intelligence as more than a mere control variable within ADHD research. The literature is limited when it comes to studies that take a closer look at what is signified by the intellectual deficits in these children. The importance of enhancing such knowledge was expressed by Nigg (2006) in the statement, “Ignoring its [intelligence] role entirely is simply not an option if we are to achieve a satisfactory, clinically meaningful understanding of ADHD” (p. 314).

As mentioned in previous sections, one of the most consistent findings in the ADHD literature is that symptoms of this disorder are associated with impaired EF. This has been evidenced in both clinical and non-clinical populations (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). EF-related components that are implicated in these findings include inhibitory functions (e.g., Barkley, 1997), WM (e.g., Rapport et al., 2008), and sustained attention or vigilance (e.g., Swaab-Berneveld et al., 2000). Barkley (1997) has proposed a theoretical model that portrays ADHD symptoms as the result of EF deficits, primarily through dysfunctional inhibitory control. In addition to these EF-related components, some lower-level non-executive functions, including the non-executive part of the WM system, that is, STM, and processing speed, have been found to be deficient in children with ADHD (e.g., Cinnamon Bidwell, Willcutt, DeFries, & Pennington, 2007; Paule et al., 2000; Shanahan et al., 2006). In summary, symptoms of inattention, impulsivity, and hyperactivity appear to be strongly associated with deficits in EF, deficits in some non-executive functions, and lower intelligence.

…And What We Know Less About: The Role of Executive Functions

Given that diverse EF components, as well as some non-executive functions have been found to be related to intelligence (Ackerman et al., 2005; Colom, Flores-Mendoza et al., 2005; Dempster, 1991; Kail & Salthouse, 1994), the literature indicates that the three phenomena ADHD, intelligence, and more specific cognitive functions (particularly EF components) are interconnected. It should be noted that these phenomena have mostly been studied in bivariate relations, and the literature is therefore largely lacking when it comes to understanding the potential mediating role of specific cognitive functions in the association between ADHD and poorer intelligence. If we are to gain more knowledge about what the association between ADHD and poorer intelligence reveals about the cognitive nature of the disorder, we must move away from the notion of intelligence as only a control variable. Instead, we should turn things around and ask whether poorer intellectual functioning in children with ADHD is mediated by specific cognitive deficits or whether the intelligence deficit tells us anything more about the disorder than the specific cognitive deficits themselves do.

Although knowledge of this type is lacking today, there are a few studies reporting results that are nonetheless relevant. Rommelse et al. (2008) showed that ADHD-related deficits in intelligence were not fully accounted for by the poorer WM and inhibitory abilities exhibited by these children. Biederman et al. (2004) demonstrated that a group of children characterized by having both ADHD *and* EF deficits showed significantly poorer intelligence compared to a group of children having *only* EF deficits and not ADHD. Although these two studies suggest that there is something more to the intellectual deficits in children with this disorder than poor EF, neither study was designed to investigate the issue of mediation of a wider range of specific cognitive deficits, and there are several obstacles to making such interpretations based on their findings.

Studying the separate ADHD symptom dimensions, inattention and hyperactivity/impulsivity, has also been proven fruitful, at least in enhancing our knowledge of the relation between EF and ADHD. Evidence that EF tasks are related particularly to the inattention dimension of ADHD has accumulated during recent years (e.g., Chhabildas, Pennington, & Willcutt, 2001; Martel, Nikolas, & Nigg, 2007; Thorell, 2007; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005) and caused some confusion among researchers: Is poorer EF really associated with increased inattention only? However, development of an EF model where so-called "hot" and "cool" EF components are defined separately (Zelazo & Müller, 2002) has led to the interpretation that both symptom domains are related to deficits in EF, although different aspects of EF are related to these domains. Most of the EF tasks used in the ADHD literature today involve relatively abstract, decontextualized problems, reflecting the "cool" EF components, and this aspect has thus been particularly implicated in inattentive symptoms. In contrast, it has been suggested that the hyperactive/impulsive behaviors are more strongly related to the "hot" EF components, characterized by problems with high affective/motivational involvement (Castellanos et al., 2006).

Extending this line of reasoning to the study of intellectual deficits in children with ADHD, it could be predicted that performance on intelligence tests, which have more similarities to the "cool" EF tasks, would be specifically related to inattentive symptoms. Although the literature is inconsistent regarding more direct support for a particular association between inattentiveness and poorer intelligence, there are some indications in favor of this notion (Chhabildas et al., 2001; Schaughency et al., 1989).

The Critical Issues of the Thesis

The Emphasis on Studying Independent Contributions

The questions investigated in the present thesis concern the relations between intelligence, EF components, and ADHD. One thing that stands out in the study of these constructs is the overlap that can be found both between the three phenomena, on the one hand, and between EF components, on the other. Briefly, based on the "unity and diversity" perspective (Miyake et al., 2000), EF components are separable but indeed related to each other, and several of these components are linked to intellectual functioning. EF and intelligence, in turn, have both been found to be related to symptoms of ADHD (Fraizer et al., 2004; Willcutt et al., 2005). The intertwined nature of these phenomena presents us with interesting research questions.

Given the overlapping constructs in this area of research, I emphasize the study of *independent* contributions throughout the thesis. I think that this approach is essential if we are to gain a better understanding of "the unity and diversity" (c.f., Miyake et al., 2000) of normal as well as malfunctioning higher-order cognition in general. In the case of studying the nature of intelligence in children (Study I and II), the independent contributions regard the different cognitive functions (primarily EF components) thought to be involved in intellectual functioning. In the case of more closely investigating the structure and function of the WM system (Study II), the independent contributions pertain to those made by the WM components in explaining intelligence. And finally, in the case of intellectual deficits in children with ADHD (Study III), deficits beyond, or independent of, poorer central EF and non-executive functions were studied.

Gaining Concurrent Understanding of Both Parties of a Relation

I would like to again highlight the point made at the beginning of this introduction, that I think we can gain a deeper understanding of the nature of both intelligence and EF by studying their relation. For example, if three EF components were found to relate independently to a measure of intelligence, this would give us information about which cognitive functions may be involved as subcomponents of intellectual functioning (see e.g., Detterman, 2000). Also, these results would provide us with data supporting the separability of these three EF components. Likewise, if the studied components were restricted to the WM system, the data would strengthen the distinctness of the studied WM components. Thus, studying relevant relations to intelligence has been proven to be very valuable in understanding both parties of the relation.

The Heart of the Matter: The Challenges of the Thesis Summarized

Among the specific cognitive functions studied in relation to intelligence, here much of the focus lies on the WM system. The theoretical as well as empirical evidence is very strong for the functional importance of this immediate memory system to human higher-order cognition (e.g., de Ribaupierre & Lecerf, 2006; Jarvis & Gathercole, 2003; Oberauer et al., 2005), and learning more about this system will result in new knowledge about human mental functioning in general. Although the WM system is relatively well studied in adults, many questions remain. In children, knowledge is even scarcer. Because of the strong emphasis in leading WM theories on the *function* of WM in higher-order cognition (see e.g., Baddeley, 2007; Engle & Kane, 2004), the information that is to be gained by future studies on the functional role of WM will be of clear relevance to theoretical developments. Given that, in today's theories of WM, the executive WM processes are assumed to be the core of WM, it is essential that we gather as much information as possible regarding their relation to other EF components, primarily inhibition. An additional motivating factor for investigating the relation between inhibitory functions and WM, particularly in children, is that these are among the more severely affected functions in children with ADHD (Willcutt et al., 2005). Thus, understanding how these processes work together in children is extremely important, and more such research on individuals both with and without ADHD is truly needed.

As discussed above, understanding the nature of intelligence is the other side of these matters. Here, the view of a general mental abilities factor (*g*; e.g., Spearman, 1927) could be roughly contrasted to a multicomponent perspective (e.g., Detterman, 2000; Thurstone, 1938). As suggested above, one way to study this issue is by using multiple regression and investigating independent contributions. Despite the fact, or maybe because of the fact, that the consensus among experts today regarding the underpinnings of intelligence is only slightly greater than it was at the beginning of the last century, this issue is very important to study. Although a more adaptive approach might have been to surrender and turn to more exciting and fresher questions, I cannot help feeling that, regardless of how long this question has been studied, it will always be one of the more pertinent research issues in the science of cognitive psychology.

Regarding questions of intellectual deficits in children with ADHD, it is essential to take into account that these children have deficits in EF and that several EF components, in turn, are related to intellectual functioning. The main issue here is that although we do know that these children generally have intellectual deficits, we do not know much about what these deficits signify. A reasonable way to begin addressing this issue would be to explore whether deficits in intelligence are mediated by deficient EF components. Information of this kind will also be relevant in the debate on whether or not intelligence should be controlled for when studying etiological factors related to ADHD.

Finally, I would like to bring together the motives for gaining more knowledge on these issues in children. Human mental abilities show striking improvement during childhood. For example, rudiments of EF have been suggested as early as in the first years of life, with an especially active developmental period between 2 and 7 years of age (e.g., Bell & Fox, 1997; Diamond & Goldman-Rakic, 1989; Eslinger, Biddle, & Grattan, 1997), and a very protracted later developmental improvement continuing during adolescence and into early adulthood (e.g., Chelune & Bauer, 1986; Luciana & Nelson, 1998; Morra, Moizo, & Scopesi, 1988; Welsh, Pennington, & Grossier, 1991). Children and adults cannot by default be considered to differ only in the quantity of a particular ability. Rather, qualitative differences are expected in many cases. It has been suggested, for example, that cognitive skills may combine at different ages to result in gradually more complex abilities (Garon et al., 2008). Achieving a coherent understanding of human cognitive functioning in general cannot be done unless the development of these functions is understood. There is also a clinical significance in studying WM and related higher-order functions in children, given that these functions are among those more deeply affected in children (and adults) with ADHD (Willcutt et al., 2005). Thus, acquiring further knowledge about the functions and interrelations of these processes in normally developing children, as well as in children with ADHD, should be highly prioritized by researchers in this area, as it can help us understand what goes wrong in some clinical cases. In sum, investigating the development of EF and related functions is critical not only to understanding children, but also to achieving a coherent theory of cognitive functioning.

Aims of the Current Thesis

The thesis is based on three studies with the overarching aims of increasing our understanding of higher-order cognitive functions in children, such as intelligence and EF components, as well as of deficiencies in intelligence found in children with the neuropsychiatric disorder ADHD. Adopting an individual-differences perspective, the studies are conducted on normally developing children within a wide age range, as well as on children with diverse psychiatric diagnoses, with a focus on ADHD.

Throughout the thesis, I emphasize the importance of studying independent contributions in order to overcome issues of overlapping constructs. The major aim was approached, first, by studying how relevant different cognitive functions, related to EF, were to intelligence, independent of each other (Study I and Study II). Although Study I emphasized WM largely in the relation to intelligence, it also included other cognitive functions allowing us to draw conclusions about the independent importance of each one of the studied functions in intelligence, as well as tentative inferences about the nature of intellectual functioning in children. Study II, on the other hand, involved only WM functions and intelligence, focusing on exploring the function and structure of WM processes in normal children. Based on the arguments presented in the introduction, these studies should yield important information on the underlying cognitive bases of intelligence in children as well as valuable knowledge about the function and interrelations of the studied EF components.

Second, we attempted to specify the intellectual deficits found in children with ADHD by studying whether such deficits are mediated by fundamental EF-related components (WM, inhibition, and sustained attention) and non-executive functions (STM and processing speed), or whether this deficit goes beyond weaknesses in these specific cognitive functions (Study III). This study was based on empirical evidence of interconnections between the phenomena of ADHD, intelligence, and EF. Investigating this issue is important because the intellectual deficit related to this disorder is a hotly disputed and highly controversial subject, and at present discussants rarely have enough meat on their bones to allow any conclusions. In other words, in order to achieve a satisfactory, clinically meaningful understanding of the concept of ADHD, we clearly need more knowledge of the implication of intellectual deficits in children with the disorder.

Empirical Studies

Participants

Study I and III are based on the same sample of children. These studies were part of the Bergen Child Study (BCS), a Norwegian longitudinal population-based study of children attending 2^{nd} to 4^{th} grade (7 to 9 years of age) in schools in the Bergen (n = 9430) and Sund (n = 222) municipalities in October 2002. The protocol and population of the BCS have been previously been described in detail (Heiervang et al., 2007; Posserud, Lundervold, & Gillberg, 2008; Stormark, Heiervang, Lundervold, Heimann, & Gillberg, 2008). The original BCS included three stages. *Stage 1*: a screening questionnaire for behavior problems and psychiatric disorders was sent to parents and teachers of the whole 7 to 9 year-old population. The questionnaire included, among other instruments, the DSM-IV diagnostic criteria for ADHD and ODD (SNAP-IV; Swanson et al., 2001); *Stage 2*: parents of all screen positive children and a random sample of screen negative children were interviewed according to the Development and Well-Being Assessment (DAWBA; Goodman, Ford, Richards, Gatward, & Meltzer, 2000), and *Stage 3*: approximately 18 months after Stage 1, 329 children together with their parents participated in an examination including a psychiatric diagnostic interview (the Kiddie-Sads-Present and Lifetime Version [K-SADS-PL]; Kaufman et al., 1997) generating DSM-IV diagnoses (American Psychiatric Association [APA], 1994) and a neuropsychological test battery. In Stage 3, children were between 8 and 11 years old. Clinicians trained in using the instrument conducted the interview, first with the parent(s) and later on the same day with the child. In accordance with K-SADS-PL directives (http://www.wpic.pitt.edu/ksads/default.htm), the diagnostic evaluation was based on information from both informants. The participants in the present study were selected among the 329 children from Stage 3, based on the criterion of completing all cognitive tasks. Two hundred and eighty-six children fulfilled this criterion. Two children were identified as having mental retardation and were therefore excluded from the sample. There were more boys (65%) than girls in this sample. One hundred and twenty-four (44%) of the children in the present sample received a psychiatric diagnosis, according to the K-SADS-PL interview.

In Study III, intelligence of children with ADHD was compared to that of children diagnosed with other psychiatric diagnoses as well as children with no psychiatric diagnoses. One child was in remission from an ADHD diagnosis, according to the K-SADS-PL interview, and was therefore excluded from the sample in Study III. Nine children who received no psychiatric diagnosis were excluded from the sample because they were in remission from some disorder. Thus, the final sample in Study III constituted 274 children. Sixty percent of the children in the final sample had screened positive for neuropsychiatric problems in Stage 1 and 40% had screened negative for such problems. There were more boys (66%) than girls in this sample. One hundred and twenty-three (45%) of the children received a psychiatric diagnosis, according to the K-SADS-PL interview. The children were assigned to one of three groups depending on their diagnostic status. Children diagnosed with an ADHD disorder, according to K-SADS-PL, regardless of the presence of comorbid diagnosis/diagnoses, were assigned to the ADHD group (n = 45; M = 10.26 years, SD = 0.75; 11% girls). Children with any diagnosis/diagnoses other than ADHD were assigned to the clinical comparison group (n = 78; M = 9.92 years, SD = 0.98; 39% girls). Children with no diagnosis were assigned to the normal comparison group (n = 151; M = 9.74 years, SD = 0.98; 39% girls). One hundred and eight children (72%) in the normal comparison group had screened negative for neuropsychiatric problems in Stage 1, and the rest had screened positive but without reaching a diagnostic level of symptoms. Thus, the majority of the children in this comparison group had low levels of neuropsychiatric symptoms, but this group also contained a minority of children with higher levels of symptoms, though not reaching clinical significance.

In Study II, one hundred and ninety-six normal children, evenly distributed between 6 and 13 years of age (55% girls) participated. Children were recruited from five different schools in and around Uppsala, Sweden. Only children in regular school classes were asked to participate. Recruitment of participants was initiated by obtaining verbal consent from school principals and teachers. Subsequently, parents were informed of the study by mail, and asked to return a written consent form.

Measures

In addition to measures of intelligence, the studies included cognitive assessment of WM components, inhibitory interference control, sustained attention, and processing speed. In Study I and II, some or all of these specific cognitive measures were used as predictor variables of intelligence, whereas the same measures in Study III were tested as potential mediators in the investigation of intellectual deficits in children with ADHD. Study III also included parent ratings of the ADHD symptom dimensions, inattention and hyperactivity/impulsivity.

Cognitive Tasks

Intelligence

In Study I and III, crystallized intelligence was defined as the sum of the age adjusted scaled scores on the Verbal Comprehension Factor, including results on the Information, Similarities, Vocabulary and Comprehension subtests of the WISC-III (Wechsler, 1992). Fluid intelligence was defined as the sum of the age adjusted scaled scores on the Perceptual Organization Factor, including results on the Picture Completion, Picture Arrangement, Block Design, and Object Assembly subtests of the WISC-III. The WISC-III is a reliable measure of intellectual ability in children aged 6-16 years (Wechsler, 1992). The Verbal Comprehension and Perceptual Organization Factors show split-half reliabilities of .94 and .90, respectively, averaged across all ages (Wechsler, 1992). The separate subtests included in these factors show reliabilities ranging from .69-.87, demonstrating adequate internal consistency.

In Study II, only fluid intelligence was assessed. Raven's Progressive Matrices (Raven, Court, & Raven, 1977) was used to measure this type of intelligence. Following test instructions, children 8 years or older performed Raven's Standard Progressive Matrices (Raven, Raven, & Court, 1998b), while children younger than 8 years performed Raven's Colored Progressive Matrices (Raven, Raven, & Court, 1998a). The 8- to 9-year-olds completed sections A-C, and the 10- to 12-year-olds completed sections A-D of the standard matrices. For the children who performed the colored matrices, all sections were completed (A, A_B, and B). In Raven's Progressive Matrices, the children are presented with pictures composed of abstract shapes, lines, and nonverbal figures, each of which is missing a piece. For each task, six or eight choices are presented and the child is to choose the piece that best fits into the empty space. The tasks did not have a time limit. The Raven's Progressive Matrices is a reliable measure of fluid intellectual ability in children and adults, with test-retest reliabilities ranging from .88 to .93, and internal consistencies ranging from .97 to 1.00 in the ages studied here (Raven, Court, & Raven, 1992). In that there are no valid Swedish age norms for performance on Raven's Progressive Matrices, and because two different tests were used across the sample, we standardized the scores within age bands spanning 1 year.

The Working Memory System

In Study I, the forward and backward versions of the Digit Span subtest of the WISC-III (Wechsler, 1992) were used to assess different components of the WM system. In these tasks, the participant is to recall and immediately reproduce sequences of digits in the same order as they were presented by the experimenter, or in the backward order. The sequences of digits increase from two to nine with two trials at each sequence length. The test stops when the participant is no longer able to correctly reproduce at least one of the two trials at a particular sequence length. This WISC-III subtest shows a split-half reliability of .85 (Wechsler, 1992).

Raw scores on the forward version of the Digit Span subtest were used to assess the short-term storage component of the WM system. Given that the executive WM component has been described as being reflected in the variance in WM tasks that is not shared with STM tasks (Engle & Kane, 2004), we extracted statistical residuals in the backward version of the Digit Span subtest by removing the variance that was shared with the forward version of the same subtest. This was done in a regression, using the forward version as predictor variable and the backward version as outcome variable. These residuals, hereafter referred to as WM residuals, were used as the measure of the executive WM component. The executive WM component has previously been commonly evaluated when controlling for short-term memory (Colom, Abad et al., 2005; Colom, Flores-Mendoza et al., 2005; Engle et al., 1999; Kane et al., 2004), which is equivalent to using WM residuals.

In Study III, the WM system was not divided into its components. Rather, all variance was kept in the backward version of the Digit Span subtest, which was used as a measure of the whole WM system. STM was, like in Study I, assessed by the forward version of the Digit Span subtest.

In Study II, we assessed both short-term storage and executive WM components, within verbal as well as visuospatial domains. The procedure for obtaining assessment of the executive WM components was equivalent to the procedure adopted in Study I, presented above. The storage component of WM was assessed using STM tasks, and the executive components of WM were assessed using statistically extracted residuals (WM residuals) in WM task variance after removing, or controlling for, the variance shared with STM tasks. The WM residuals were calculated in separate regression analyses, with each WM measure as the outcome variable and the modality-matching short-term storage measure as the predictor.

Verbal STM was assessed using a word span task, based on the Digit Span subtest of the WISC-III (Wechsler, 1992). In this task, series of words were orally presented to the child by the experimenter at a rate of one word per second. We used one- or two-syllable words that denoted common objects judged to be familiar to children within the given age range (e.g., rabbit, hat, eye). The child was to remember the words in the same order in which they were presented, and to repeat them back to the experimenter immediately after each sequence. Trials increased from two to seven words, with two trials at each list length. For a trial to be considered correct, all words in that sequence had to be remembered in the correct order. Testing continued as long as the child managed to correctly repeat at least one of the two trials at a particular list length. The span score, which was used as a measure of verbal STM, was calculated as the sum of correct trials. Adequate test-retest reliability of .67 for this test has been reported by Thorell and Wåhlstedt (2006).

In the visuospatial STM task used in Study II, figures in the form of identical beach balls were presented one at a time in different locations on the computer screen. In order to minimize the probability of verbal encoding of the locations of the beach balls, the stimuli were presented on an empty screen instead of within a grid. On a computer screen measuring 28 cm, the beach balls measured 1.7 cm in diameter, with a filled circular yellow frame around them that was 2.5 cm in diameter. The child was to remember the locations of the beach balls in the same order as they were presented and, after each trial, to use the computer mouse to mark the remembered locations. Trials increased from two to six locations, with three trials at each level. One score was given for each consecutive pair of locations that was remembered in the correct order. Thus, one point was given for correct marking of the locations of the first and second beach ball. A second point was given for correct marking of the locations of the second and third beach ball, etc. In this way, a trial consisting of 4 beach balls gave a maximum of three points. The span score, used as a measure of visuospatial STM, was calculated as the sum of scores across trials. A response within a radius of 18 mm from the perimeter of the yellow circular frame was considered a correct marking. The radii of the targets presented within the same trial never overlapped. In order to obtain enough data from our youngest participants, all children completed the first seven trials (up until the first trial with four locations to remember), regardless of how many scores they had obtained. After the first seven trials, the test automatically stopped if the child had not managed to obtain a minimum of 30% of the maximum number of scores on each trial. Reliability data for this measure was obtained by calculating the correlation between the sum of scores on the first trails on each level and the sum of scores on the second trials on each level. This revealed a reliability of .73.

In The Children's Size Ordering Task (CSOT) (McInerney, Hrabok, & Kerns, 2005), the word span task is modified so that the child is to repeat the objects back to the experimenter in *order of size* from smallest to largest. This task was used as a measure of verbal WM. Different, but equally common, nouns from those employed in the word span task were used in the CSOT. One score was given for each consecutive pair of objects that was remembered in the correct order. Thus, one score was given for correct reproduction of the first and second object, and a second score was given for correct reproduction of the second and third object, etc. In this way, a trial consisting of 4 objects gave a maximum of three points. Trials increased from two to seven objects, with two trials at each list length. The span score was calculated as the sum of scores across trials. Testing continued as long as the child was able to obtain at least one score on one of the trials at a particular list length.

In order to assess visuospatial WM, the visuospatial STM task was modified to include manipulation similar to that of the verbal WM task. In other words, the beach balls that appeared on the computer screen in the visuospatial WM task were of different sizes (from 0.4-2.0 cm in diameter) against the yellow background frame, and the children were to indicate, using the computer mouse, the locations of the beach balls in their *order of size*, starting with the location of the smallest beach ball. Trials increased from two to six locations, with three trials at each level. The six different sizes of the beach balls were perceptually easily distinguished from each other. The scoring procedure corresponded to that used for the visuospatial STM task. Reliability for this measure, obtained in the same way as in the visuospatial STM task, was .72.

Inhibitory Interference Control

This function was assessed by interference scores derived from the Stroop task and the Attention Network Task (ANT). In the present paper-and-pencil version of the Stroop task (Lund-Johansen, Hugdahl & Wester, 1996), the participant is presented with color patches or color words, printed either in compatible or incompatible ink color (e.g., the word "red" is printed in either red or blue) on separate sheets. The participant was instructed to say the ink color of each word or color patch, which produces a response conflict on the trials where the ink color is incompatible with the meaning of the word. Interference scores in the Stroop task were calculated by subtracting the number of errors made in the color patch condition from the number of errors made in the incompatible word-color condition. Split-half reliability of computerized versions of the Stroop task on adults has been reported to be .80, and thus adequate (Friedman & Miyake, 2004).

The ANT used in the present study is the original “child version” (Rueda et al., 2004). The test has four cue conditions (no cue, center, double, orienting) and three flanker conditions (congruent, incongruent, neutral), and has been described in detail elsewhere (Mezzacappa, 2004; Rueda et al., 2004). All combinations of conditions were randomly presented in three blocks of 48 trials each. The participants were instructed to indicate which direction a fish was pointing by pressing the left or right mouse button with their corresponding thumb. Sometimes the fish appeared alone, and at other times it appeared in the middle of a row of 5 identical fish. The participant was told to respond to the fish in the middle of the row. The flanking fish either pointed in the same direction (congruent) or in the opposite direction (incongruent) as the target fish in the middle. Test-retest reliability of the ANT has been demonstrated to be adequate, .77 (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Interference scores in the ANT were calculated by subtracting the number of errors made in the congruent target-flanker condition from the number of errors made in the incongruent target-flanker condition, across all cue conditions.

No interference scores in either the ANT or the Stroop task were negative, which would indicate that more errors were made in the congruent conditions than in the incongruent conditions. The ANT and Stroop interference scores were significantly correlated ($r = .15$, $p < .05$), and were aggregated after standardization into the interference control composite measure that was used in the analyses in Study I and III.

Sustained Attention

Sustained attention was assessed by Conners’ CPT (Conners, 1994), in which participants are instructed to respond to all letters presented on the computer screen, except for the letter X, for 14 minutes. Split-half reliabilities for the different performance measures on this CPT range between .73 and .95 (Conners, 2000). In addition, test-retest reliabilities for a 3-month interval range between .55 and .84 (Conners, 2000). Both indices suggest adequate reliability for this test. The test is divided into six time blocks, which enables calculation of the slope of change in performance across time on task, in either a positive (i.e., increased values) or negative slope (i.e., decreased values). This has been suggested to be essential if conclusions are to be drawn regarding *sustained* attention (Nigg, 2006; van der Meere & Sergeant, 1988). The measures used in this study to assess sustained attention were standard error of reaction time on hits (RTSE), the slope of change of hit RT, and the slope of change of hit RTSE. These measures were significantly correlated (r = .40-.63) and were therefore aggregated, after standardization, to form the variable sustained attention, where higher values indicate poorer sustained attention.

General Processing Speed

General processing speed was assessed by the sum of the age adjusted scaled scores on the Processing Speed Factor of the WISC-III (Wechsler, 1992), comprising results on the Coding and Symbol Search subtests. In the Coding subtest, participants are to copy simple symbols and match these with digits as quickly as possible. On each item in the Symbol Search subtest, a row of abstract symbols are presented. The participants are asked to decide as quickly as possible if target symbols appear in the row of symbols by checking a "yes" or "no" box. The Processing Speed Factor shows test-retest reliability of .88 (Wechsler, 1992).

Ratings of ADHD Symptoms

In Study III, the two symptom dimensions inattention and hyperactivity/impulsivity of ADHD were assessed in all children and controlled for in one step of the analyses. In the screening phase (Stage 1) of the longitudinal study that Study III was a part of, the behavioral problems of all children were assessed using a modified version of SNAP-IV (Swanson et al., 2001), filled in by both parents and teachers. These items are identical to the items in the SNAP-IV, except that SNAP-IV uses four levels to evaluate each item, whereas in our study we used three levels: *not true*, *somewhat true*, and *certainly true*. This change was made to adapt the scores to those used in the other scales included in the questionnaire. The inattention and hyperactivity/impulsivity scales each consisted of the nine items used to define the ADHD diagnosis in the DSM-IV system. Internal consistency of both scales in this study were $\alpha = .91$. The parent rather than teacher ratings were chosen to correspond to the informants in the K-SADS-PL interview, which was based on parent (and child) data. The mean scores on the scales were used in the analyses. The ADHD behavior information from the screening phase was collected approximately one and a half years before the children were assessed with the K-SADS-PL and neuropsychological tests in Stage 3.

Study I

Working Memory Components, Interference Control, Sustained Attention, and Processing Speed as Independent Predictors of Intelligence in Children

Background and Aims

The issue of which specific cognitive functions are essential to intelligence and which are not is currently challenging the literature on intelligence (see e.g., Friedman et al., 2006). Functions such as working memory, attention, and inhibitory have been suggested to be relevant to this research. Many of these predictors overlap considerably both theoretically and operationally, which requires the inclusion of several of these phenomena in the same study to evaluate their individual, independent contributions to intelligence. Research of this type on children is particularly scarce.

The aim of the present study was to investigate whether the cognitive functions of short-term storage and executive components of WM, inhibitory interference control (i.e., inhibition of distracting stimuli), sustained attention, and processing speed were independently related to intelligence in children 8-11 years of age. Such data should yield valuable knowledge a) about the interrelations and independence of the cognitive functions used as predictors, b) about the independent importance of each one of the studied functions in intelligence, and c) about the underlying cognitive bases of intelligence in children. First, we investigated the independent contributions of, theoretically based, subsets of functions (see, Table 1). Second, we studied independent contributions of all cognitive functions simultaneously. Based on results from our previous study on children (Tillman, Nyberg, & Bohlin, 2008), we hypothesized that both the short-term storage and executive components of the WM system would make significant, independent contributions to the explained variance in intelligence. Rooted in indications from developmental research of WM and inhibitory functions being relatively independent in children (Diamond, 2006; Garon et al., 2008), we hypothesized that the executive component of WM and interference control would predict independent parts of the variance in intelligence. Based on conceptual independence and assumptions of task demands on sustained attention in the other cognitive tasks, sustained attention was predicted to account for some, but not all, variance in the relations between intelligence and the other cognitive functions. Sustained attention was also predicted to make an independent contribution on its own.

Results

The measures that were not age standardized scaled scores from the WISC-III were cleared of age-related variance, by extracting statistical regression residuals in each variable by removing the variance shared with child age. These residuals were used in all subsequent analyses. All intercorrelations were significant (all *p*s < .01) except for the correlation of WM residuals with short-term storage (this correlation should by definition be 0), interference control, and sustained attention. There were significant sex differences on several measures including the outcome measure fluid intelligence (*t*s ranging 1.99-5.82, *p*s < .05), with girls performing at a higher level than boys. As a consequence, all subsequent analyses using fluid intelligence as dependent variable controlled for sex.

Results of the multiple regressions investigating independent contributions of the different cognitive functions can be found in Table 1. We first studied independent contributions of the two WM components, short-term storage and the executive WM component (as reflected in the WM residuals), and found that both components explained significant, independent portions of the variance in both crystallized and fluid intelligence ($R^2_{crystallized} = .23$; $R^2_{fluid} = .17$) (see, Analysis 1 in Table 1). Control for sustained attention resulted in somewhat weakened relations, which however were still highly statistically significant. Next, we turned to the inhibitory interference control measure and the WM residuals, and found that they made significant independent contributions to both crystallized and fluid intelligence ($R^2_{crystallized} = .13$; $R^2_{fluid} = .18$) (see, Analysis 2 in Table 1). Although these relations weakened somewhat when controlling for sustained attention, they remained highly significant. Finally, we looked at the independent contributions of all four variables short-term storage, WM residuals, interference control, and sustained attention. In this analysis, we were particularly interested in studying the unique contribution of sustained attention. Regarding both crystallized and fluid intelligence, sustained attention as well as the other variables made significant independent contributions (see, Analysis 3 in Table 1). Twenty-nine percent of the variance in crystallized intelligence and 24% of the variance in fluid intelligence was explained by all of these predictor variables. This meant that 9% of the variance in crystallized intelligence and 8% of the variance in fluid intelligence was accounted for by the shared variance among the predictors.

The conclusions of the analysis with all cognitive variables included were only slightly affected by adding general processing speed as a covariate. The minor changes were that the relations of fluid intelligence with short-term storage, ß = .10; $p = .07$, and sustained attention, ß = -.10; $p = .06$, fell short of significance. All other relations were still significant. Important to note is that processing speed did contribute unique variance, beyond the contributions of the other variables, to the explanation of crystallized intelligence, ß = .14, $p < .05$, as well as in fluid intelligence, ß = .26, $p < .001$. In these models, 31% of the variance in crystallized intelligence and 29% of the variance in fluid intelligence was accounted for by the predictor variables. Lastly, all analyses were rerun with a variable representing the presence of a diagnosis (coded as 0 or 1) as covariate. The results did not change when controlling for the presence of a diagnosis.

Conclusions

In this study we emphasize the importance of studying independent contributions of different suggested predictors of intelligence so as to overcome issues of overlapping constructs. The general finding that short-term storage, the executive WM component, interference control, sustained attention, and processing speed were independent predictors of intelligence in children is important per se, as it implies validity and strength to the bivariate relations evidenced in previous work. More specific conclusions drawn from this result were that a) the WM components are separable in children, b) inhibitory blocking of interference and executive WM functions are described as independent of each other in children, and c) intellectual functioning in children may be best viewed as multifactorial. This finding is in line with the argument by Detterman (2000) that *g* does not represent a single underlying entity, but rather is made of further separable basic cognitive processes. Shared variance between the predictors in the explanation of intelligence was evident, however, which could possibly indicate that there is also some kind of common resource reflected in intellectual functioning.

Table 1. *Beta Values, Standard Error of B, and Squared Semi-Partial Correlations (sr^2) in the Regression Analyses Investigating Independent Contributions of Short-Term Storage, WM Residuals, Inhibitory Interference Control, and Sustained Attention in the Prediction of Crystallized and Fluid Intelligence. Independent Contributions are Interpreted Within each of the Three Analyses. Within Parentheses are Values when Controlling for Sustained Attention*

Predictor variables	*Outcome variables*					
	Crystallized intelligence			Fluid intelligence		
	ß	*SE B*	sr^2	ß	*SE B*	sr^2
Analysis 1						
Short-term storage	.40*** (.35***)	0.31 (0.31)	.16 (.11)	.25*** (.20***)	0.34 (0.35)	.06 (.04)
WM residuals	.26*** (.23***)	0.40 (0.39)	.07 (.05)	.30*** (.28***)	0.44 (0.44)	.09 (.08)
Analysis 2						
Interference control	-.27*** (-.19**)	0.72 (0.73)	.07 (.03)	-.27*** (-.23***)	0.70 (0.72)	.07 (.05)
WM residuals	.23*** (.21***)	0.43 (0.42)	.05 (.04)	.27*** (.27***)	0.44 (0.43)	.07 (.07)
Analysis 3						
Short-term storage	.33***	0.31	.10	.17**	0.34	.03
WM residuals	.22***	0.39	.05	.28***	0.43	.07
Interference control	-.14*	0.69	.02	-.20***	0.71	.04
Sustained attention	-.19**	0.68	.03	-.15*	0.73	.02

Note. n ranges from 279-283. Sex was used as a covariate in the analyses with fluid intelligence as outcome variable (see, Results Section).
* $p < .05$, ** $p < .01$, *** $p < .001$

Study II

Working Memory Components and Intelligence in Children

Background and Aims

In this study, we focused on the WM system in relation to intelligence in children. WM has consistently been shown to be strongly linked to reading comprehension, mathematical ability, and fluid intelligence in both children and adults (see e.g., Oberauer et al., 2005, for a meta-analysis; Gathercole & Baddeley, 1993; Jarvis & Gathercole, 2003; Logie, Gilhooly, & Wynn, 1994; Pickering & Gathercole, 2004). According to the WM theory proposed by Engle and Kane (2004), the WM system is composed of a short-term storage component and an executive WM component. Based on this theory, it has been argued that the executive WM processes are reflected in the variance in WM performance that is not shared with STM performance. An important question is to what extent these different WM components are involved in the manifestation of higher-order cognition. The literature on individual differences in WM in children is limited, especially regarding how WM is related to intelligence.

Based on the Engle and Kane theory of WM, the present study involved four tasks used to combine the two factors of modality (verbal vs. visuospatial) and presence of executive demands (short-term storage vs. short-term storage + executive WM processes). Two simple span tasks were used to assess verbal and visuospatial short-term storage. To assess verbal and visuospatial short-term storage + executive WM processes, or WM, the two simple span tasks were modified to entail comparable manipulation of the to-be-remembered material. This design enabled us to, relatively purely, statistically isolate short-term storage and executive WM processes within each domain. The executive WM processes were isolated by extracting *WM residuals*, that is, WM performance after removing the variance shared with short-term storage performance within each modality. The main aim of the present study was to examine the relative functional importance of different components of WM, within verbal and visuospatial domains, to fluid intelligence. The data obtained here were also interpreted in terms of what information they could give us about the structural organization of the WM system in children.

Results

There were significant positive correlations between all memory variables (all *p*s $< .01$) except between verbal and visuospatial STM, for which the correlation was nearly significant ($p = .053$). The correlations between short-term storage and domain-matching executive WM processes are by definition 0. Intelligence was significantly related to all memory variables (all *p*s < .01). Due to significant age effects on all memory variables (the intelligence measure was standardized within separate age groups), statistical residuals were extracted in these measures by removing the variance shared with child age. These residuals were used in all subsequent analyses.

To investigate the relative role of short-term storage and executive WM processes in predicting intelligence, standard regression analyses were performed. The verbal or visuospatial short-term storage measure was entered together with the domain-matching WM residuals in separate analyses. The results showed that, in this model, verbal short-term storage, $\beta = .27$, $t = 4.05$, $p < .0001$, $sr^2 = .07$, and verbal WM residuals, $\beta = .24$, $t = 3.53$, $p < .001$; $sr^2 = .06$, both significantly predicted intelligence independent of each other, $F\ (2, 191) = 14.42$, $p < .0001$. Similarly, for the visuospatial domain, short-term storage, $\beta = .21$, $t = 3.09$, $p < .01$, $sr^2 = .04$, as well as WM residuals, $\beta = .24$, $t = 3.50$, $p < .001$, $sr^2 = .06$, made significant independent contributions to the explanation of intelligence, $F\ (2, 191) = 10.91$, $p < .0001$.

To investigate the specificity of verbal and visuospatial short-term storage in the prediction of intelligence, these two measures were entered simultaneously into a standard regression equation with intelligence as the outcome variable. Verbal short-term storage, $\beta = .25$, $t = 3.59$, $p < .001$, $sr^2 = .06$, and visuospatial short-term storage, $\beta = .18$, $t = 2.57$, $p < .05$; $sr^2 = .03$, were significantly related to intelligence independently of each other, $F\ (2, 191) = 11.25$, $p < .0001$. Next, we investigated the independent contributions of the verbal and visuospatial WM residuals to the explanation of intelligence. Analogous to the results on short-term storage, the verbal WM residuals, $\beta = .19$, $t = 2.70$, $p < .01$, $sr^2 = .03$, as well as the visuospatial WM residuals, $\beta = .19$, $t = 2.73$, $p < .01$; $sr^2 = .04$, were significantly related to intelligence independent of each other, $F\ (2, 191) = 9.70$, $p < .0001$. In line with the results described above, all four WM components made significant, independent contributions to the explained variance in intelligence (verbal short-term storage, $\beta = .22$, $t = 3.16$, $p < .01$, $sr^2 = .04$; visuospatial short-term storage, $\beta = .15$, $t = 2.12$, $p < .05$; $sr^2 = .02$; verbal WM residuals, $\beta = .17$, $t = 2.45$, $p < .05$, $sr^2 = .03$; visuospatial WM residuals, $\beta = .15$, $t = 2.10$, $p < .05$; $sr^2 = .02$; $F\ (4, 189) = 9.49$, $p < .0001$). Seventeen percent of the variance in intelligence was explained by these four variables.

Conclusions

This study has shed light on the roles played by the different WM components in predicting intelligence in children by indicating the equal and independent importance of short-term storage and executive WM processes within both verbal and visuospatial domains. Our findings in children also suggest structural domain-specificity of the executive WM processes, a notion that has caused lively debate in previous research on adults (see e.g., Fletcher & Henson, 2001; Kane et al., 2004; Mackintosh & Bennett, 2003; Shah & Miyake, 1996). Further, we found support for the notion of separate short-term storage and executive WM processes in the structural organization of the WM system. As emphasized throughout this paper, few previous studies have looked at systematic separation of the different components within the verbal and visuospatial domain of the WM system, particularly in children. The present study helps to fill this gap, but more research on both children and adults is clearly needed. Most importantly, the challenge of exploring the nature of the variance left in WM after its storage component has been partialled out should be taken on by future research.

Study III

Intellectual Deficits in Children with ADHD Beyond Central Executive and Non-Executive Functions

Background and Aims

Children and adolescents with Attention Deficit Hyperactivity Disorder (ADHD) have been shown to have deficient cognitive functions, including EF components (Willcutt et al., 2005) and intelligence (Fraizer, et al., 2004). Given that diverse EF components are also related to intelligence (Ackerman, et al., 2005; Dempster, 1991; Salthouse, Atkinson, & Berish, 2003; Tillman, Bohlin, Sørensen, & Lundervold, 2007), the three phenomena ADHD, intelligence, and EF are empirically interconnected. It should be noted that these phenomena have mostly been studied in bivariate relations, and the literature is therefore largely lacking regarding understanding of how *all three* phenomena are interrelated. We ask whether poorer intellectual functioning in children with ADHD is mediated by specific cognitive deficits or whether the intelligence deficit tells us anything more about the disorder than the specific cognitive deficits themselves do. And if it does tell us something, *what* does it tell us? These issues have not previously been studied in a systematic and comprehensive way.

The main aim of the study was to specify the deficit in intellectual ability in children with ADHD by adopting a mediation perspective. We studied whether such an intellectual deficit is mediated by fundamental EF related components (WM, inhibition, and sustained attention) and non-executive functions (STM and processing speed), or whether this deficit goes beyond deficits in these specific functions. Mediation was considered supported if the group difference in intelligence was no longer significant when the potential mediators were entered as covariates. Performance of children diagnosed with ADHD was studied relative to that of children with other psychiatric diagnoses as well as children with no psychiatric diagnosis. In that the issue pertaining to the mediating role of specific cognitive functions in intellectual deficits in children with ADHD is still explorative in nature, we did not state any predictions. We further approached the question of what an intellectual deficit in these children may signify by studying which of the symptom dimensions, inattention and hyperactivity/impulsivity, was driving the intellectual deficits.

Results

The measures that were not age standardized scaled scores from the WISC-III were cleared of age-related variance, by extracting statistical regression residuals in each variable by removing the variance shared with child age. These residuals were used in all subsequent analyses. The ADHD group performed significantly below the clinical comparison group and the normal comparison group on all executive as well as non-executive functions (*F*s ranging 3.50-7.03). All cognitive functions were significantly related to both crystallized and fluid intelligence as well as to each other (all ps $< .05$). There were significant sex differences on several measures including the outcome measure fluid intelligence (*t*s ranging 2.11-5.67), with girls performing at a higher level than boys. As a consequence, all subsequent analyses using fluid intelligence as dependent variable controlled for sex.

Results from the analyses investigating potential mediating factors in the group differences in intelligence are presented in Table 2. The ADHD group obtained significantly lower intelligence scores compared to both the normal and the clinical comparison groups, when no potential mediators were included. The effect sizes were medium (Kirk, 1996). When entering each one of the potential mediators, the ADHD group still showed significantly poorer crystallized as well as fluid intelligence compared to the normal comparison group and clinical comparison group. ADHD-related deficits in intelligence were thus not mediated by any one of the specific cognitive functions alone.

When entering all EF-related components and non-executive functions simultaneously as potential mediators, the ADHD group still had significantly poorer fluid intelligence compared to the normal comparison group and the clinical comparison group, with effect size in the small range. In other words, full mediation was not obtained. Instead, a difference in intelligence that could not be explained by deficiencies in the included cognitive functions was observed. In contrast, for crystallized intelligence there were no significant group differences when all of the cognitive functions were covaried simultaneously, indicating full mediation. These results held when controlling for ODD.

Because we only found evidence for an intellectual deficit in the ADHD group beyond deficits in the studied cognitive functions, regarding fluid abilities, the analyses investigating the role of the ADHD symptom dimensions in this deficit were only conducted with regard to fluid intelligence. The ADHD group still performed significantly worse compared to the normal comparison group and the clinical comparison group when hyperactivity/impulsivity as well as when inattention was controlled for (ps $< .05$). These results did not change when controlling for ODD.

Conclusions

Using a mediation approach, this study has revealed intriguing new information about what intellectual deficits in children with ADHD tell us about the disorder. We have shown that, regarding fluid intelligence, the intellectual deficits are not mediated by, but rather go beyond, weaknesses in central EF-related components and non-executive functioning, with regard to WM, inhibition, sustained attention, STM, and processing speed. We tentatively interpret these fluid deficits as reflecting deficiencies in a general intellectual resource. Concerning crystallized ability, in contrast, the deficit signifies poor abilities in these aspects of cognitive functioning, as indicated by their effectiveness as mediators. The fluid intellectual deficits that were not accounted for by deficiencies in the specific cognitive functions appeared to be related to both hyperactivity/impulsivity and inattention symptoms. The differences between crystallized and fluid intelligence in ADHD-related impairments point to the value of studying these intelligence types separately, particularly in studies of ADHD. In conclusion, the results indicate that the significance of intelligence in ADHD should not be limited to a mere control variable in analyses studying etiological factors, but should rather be viewed as holding critical information about the disorder per se.

Table 2. *Least Square Means (LSM), Standard Errors (SE), and Results From the Analyses Investigating Group Differences in Intellectual Ability, as well as Potential Mediators*

		Group								
		ADHD n = 45		CC n = 78		NC n = 150				
Covariate	*Dependent measure*	LSM	SE	LSM	SE	LSM	SE	F	Partial η^2	Planned contrasts
-	C. intelligence	28.36	1.34	33.76	1.02	34.47	0.73	8.20***	.06	ADHD< NC, CC
	F. intelligence	31.08	1.38	37.70	1.03	38.38	0.75	10.95***	.08	ADHD< NC, CC
WM	C. intelligence	29.87	1.26	33.23	0.95	34.29	0.68	4.72**	.03	ADHD< NC, CC
	F. intelligence	32.23	1.31	37.24	0.97	38.26	0.70	8.16***	.06	ADHD< NC, CC
Inhibition	C. intelligence	29.06	1.32	33.68	0.99	34.30	0.72	6.14**	.04	ADHD< NC, CC
	F. intelligence	31.79	1.35	37.62	1.00	38.20	0.72	8.83***	.06	ADHD< NC, CC
Sustained attention[a]	C. intelligence	29.78	1.32	33.45	0.96	34.28	0.70	4.50**	.03	ADHD< NC, CC
	F. intelligence	32.36	1.41	37.51	1.01	38.34	0.74	7.00**	.05	ADHD< NC, CC
STM	C. intelligence	29.89	1.26	33.36	0.94	34.21	0.68	4.55*	.03	ADHD< NC, CC
	F. intelligence	31.81	1.37	37.50	1.01	38.26	0.73	8.62***	.06	ADHD< NC, CC
Processing speed	C. intelligence	29.78	1.29	33.87	0.96	33.98	0.70	4.35*	.03	ADHD< NC, CC
	F. intelligence	32.21	1.30	37.92	0.96	37.92	0.70	7.93***	.06	ADHD< NC, CC
All five functions	C. intelligence	31.67	1.22	33.15	0.88	33.90	0.64	1.31	.01	
	F. intelligence	33.77	1.29	37.46	0.92	37.97	0.67	4.14*	.03	ADHD< NC, CC

Note. CC = clinical comparison group; NC = normal comparison group. C. intelligence = crystallized intelligence; F. intelligence = fluid intelligence. Sex was used as a covariate in the analyses with fluid intelligence as outcome variable (see, Results Section).
[a]n for this measure was 42 for the ADHD group and 146 for the normal comparison group, due to missing data
* $p < .05$, ** $p < .01$, *** $p < .001$

General Discussion

The present thesis is built on three studies with the fundamental aim of improving our understanding of higher-order cognitive functioning in normally developing children, as well as of deficits in these cognitive functions in children with ADHD. Based on an individual-differences perspective, this was achieved by studying whether different EF components, focusing on WM, were independently related to intelligence, and whether intellectual deficits in children with ADHD go beyond certain deficient EF and non-executive functions. When investigating these issues, a better understanding can be achieved of the outcome variable intelligence, which characterizes "ultimate" higher-order cognition, as well as the predictor variables, here represented by EF components and ADHD. First, I will summarize the main findings. Second, I will discuss what the findings indicate about the make-up and interrelations of specific EF-related processes as well as what they imply about the nature of intelligence in children. Third, I will consider the contributions of the thesis regarding the issue of what intellectual deficits in children with ADHD can teach us about the nature of this disorder. I will conclude with some take-home messages including proposals for future research.

The Heart of the Thesis: Key Findings

Of the specific cognitive functions studied as predictors of intelligence, WM is in the spotlight of the present thesis. Study I and II were both designed to fill a gap in the literature by providing detailed data on the function and structure of the WM system in children. Both studies adopted theoretically based means of statistically separating short-term storage and executive WM processes in STM and WM performance, which allowed us to draw more valid conclusions about the different WM components compared to previous studies. Together these two studies demonstrated that both short-term storage and executive components of the WM system, within verbal as well as visuospatial domains, made independent contributions to the explanation of intelligence. For fluid intelligence, all components were equally important, but for crystallized intelligence, short-term storage processes appeared to be more relevant. These findings support the notion that these components are structurally as well as functionally distinct in children aged 6-13 years. Especially intriguing is the finding indicating that verbal and visuospatial executive WM processes appear to be separable in children, an issue that has caused heated exchanges in the literature on adults (see e.g., Fletcher & Henson, 2001; Kane et al., 2004; Mackintosh & Bennett, 2003; Shah & Miyake, 1996). We further showed that the relations between WM components and intelligence were not accounted for by shared task demands on sustained attention, and that inhibitory interference control and the executive WM component were independent regarding their relations to intelligence. This latter finding is interesting viewed in light of the idea of developmental change in the relation between EF components (Garon et al., 2008).

Study I also yielded important information regarding the constitution of intelligence in children. We demonstrated that short-term storage, executive WM processes, inhibitory interference control, sustained attention, and processing speed were independently related to intelligence in children aged 8-11 years. This finding was interpreted as support for a multifactorial nature of intelligence in children (e.g., Detterman, 2000; Thurstone, 1938). Due to shared variance between the predictors in the explanation of intelligence, there may also be some kind of common resource reflected in intellectual functioning.

Study III was intended to extend the findings on normal intellectual functioning from Study I and II by investigating clinically relevant intellectual deficits in children with ADHD. We provided evidence for deficient fluid intelligence in these children that is not mediated by relevant specific cognitive functions. In other words, these intellectual deficits appear to signify something beyond the poorer functioning of the EF-related components – WM, inhibition, and sustained attention – and the non-executive components – STM and processing speed. In contrast, in the case of crystallized intelligence, mediation was evident, meaning that crystallized deficits indicated no more than weakness in these specific functions.

The Nature of the WM System in Children

The fact that WM is theoretically strongly implicated in other higher-order cognitive functions, such as intelligence, reading comprehension, and mathematical abilities, is really no surprise, given that it is inherent in the definition of this immediate memory system that it is concerned with memory *at work*, in the service of complex cognition (e.g., Baddeley, 2007; Conway et al., 2007). Similarly, the strong empirical evidence for such associations also leaves no doubts about the fact that WM is important in higher-order cognitive functioning. However, because WM is a broad higher-order construct, we need to specify which specific cognitive processes are responsible for the functional role of WM in, for example, intelligence. This issue could be approached from a number of different perspectives and at different levels of explanation. The approach chosen here primarily regards the study of the relative importance of theoretically based components of the WM system for intellectual functioning.

What Have We Learned About the Function of WM?

Our results indicate that both the function of short-term storage and executive WM processes, within the verbal as well as the visuospatial domain, are important to intellectual functioning in children. Although this is the first study on children investigating the issue of the relative importance of the WM components in intellectual functioning, our results are consistent with findings from several studies on adults (Colom, Abad, et al., 2005; Colom, Rebollo, Abad, & Chun Shih, 2006; Shah & Miyake, 1996).

However, there are also studies contradicting the notion of the equal importance of the WM components. For example, a study by Engle et al. (1999) concluded that only executive WM processes were important to intelligence in adults. Given the different populations investigated in Engle et al.'s study and our study (adults vs. children), an initial interpretation would perhaps be that the differences in results are related to development. If we take a closer look at the operational and statistical procedures used in these studies, however, it appears as if methodological factors represent a more likely explanation for the contradictory findings. In Engle and colleagues' statistical analyses, intellectual functioning was predicted simultaneously by STM and WM tasks, which according to their own logic should remove short-term storage processes from both types of measures. It could therefore be argued that the role of short-term storage was not even investigated. Indeed, before controlling for the common variance with WM, Engle et al. found that the STM tasks were correlated with intelligence. Similar critical arguments can be made about other studies supporting the primary role of executive WM processes in intellectual functioning in adults (cf., Kane et al., 2004). Further support for the importance of operational strategies for the results comes from a reanalysis of five key data sets (Colom et al., 2006; the reanalysis included Engle et al., 1999 and Kane et al., 2004). By constructing separate factors for storage processes and for the residual variance in WM tasks (reflecting executive WM processes), they gave short-term storage a fair chance to correlate with intelligence. The differences in results compared to the original studies were striking. In the reanalysis, a much stronger role in relation to intelligence was attributed to the storage processes. In other words, previous findings supposedly providing support for the primary importance of the executive WM processes in complex cognition might have been caused by not "allowing" short-term storage processes to correlate with measures of complex cognition.

The Role of Short-Term Memory

I would like to make clear that I have no doubts about the importance of executive WM processes in complex cognition such as intelligence. The theoretical hypothesis that WM is memory with the major purpose of aiding complex cognition cannot be overlooked, and the extensive empirical evidence in favor of the executive WM processes is too strong. But I do not think that these processes, exclusively, can tell the whole story about the strong relation between WM and intelligence. We must not underestimate the role of simple maintenance of information in intellectual functioning. However, we should not be satisfied with such a simple conclusion regarding STM. Rather, in line with my arguments about the importance of specifying what it is in executive WM processes that drives the relation to complex cognition, we should also dig deeper into the role of STM processes. In the present thesis, I have provided information suggesting that these processes are worth taking a closer look at. Although our data do not really allow any further interpretations about the more specific STM-related processes that could be responsible for the evidenced link between STM task performance and intelligence, I feel tempted to present some tentative speculations.

Colom and colleagues strongly maintain the position that memory span tasks (both STM and WM tasks) and intelligence exhaust the same single general purpose resources, which is interpreted as the ability to temporarily maintain a reliable mental representation of information from any kind of task – that is, STM (Colom, Abad, et al., 2005; Colom & Chun Shih, 2004; Colom et al., 2006). It should be underlined that the perspective of Colom and coworkers is extreme in that they to the greatest extent possible emphasize *only* storage processes as important in WM. Unfortunately, these authors have not provided a discussion of their extreme view within a more general framework of human mental functioning and cognitive control. The vagueness of their definition of the common resource and the lack of actual meaningful implementation of STM in a larger context of complex cognition limit the explanatory value of their view.

A more informative explanation of what might account for the relation between STM tasks and intelligence could be offered by the theory proposed by Hasher and colleagues (e.g., Hasher, Lustig, & Zacks, 2007). They maintain that one of the limiting factors in WM is the ability to inhibit or disregard distraction coming from information that was previously relevant but no longer is (referred to by Hasher et al. (2007) as "deletion" and by Friedman et al. (2004) as "resistance to proactive interference"). Resistance to proactive interference could be interpreted as crucial not only in WM tasks, but also in STM tasks. In other words, there is no reason to believe that items recalled in previous trials of memory span tasks should be any more, or less, disturbing in tasks involving processing or manipulation demands (i.e., WM tasks) than in simple span tasks (i.e., STM tasks). Based on this interpretation, it may thus be the processes responsible for the deletion of information that is no longer relevant that drive the relation between STM tasks and intelligence.

Executive WM Processes and Inhibitory Interference Control

At this point, I feel that STM in intellectual functioning has received the attention it deserves, and I will now turn to the executive WM component. In Study I, we investigated the relation between the executive WM component and interference control, by studying their potential independent contributions made to intelligence. Interference control has previously been indicated to be separate from the above-discussed inhibitory function, resistance to proactive interference (Friedman et al., 2004). Before getting into this discussion, I would also like to remind the reader that the WM tasks used in the present studies did not aim to capture the entire integrative nature proposed for the executive attention processes (see, p. 13-15 in this thesis). Rather, these tasks intended to primarily tap cognitive processes responsible for working with maintained information.

Our result showing independent contributions of interference control and the executive WM component in the prediction of intelligence is in keeping with our hypothesis of relative independence of these two functions in children, which was based on the developmental model proposed Diamond (e.g., 2006). Diamond has maintained that inhibition and WM are two central, separate EF components, and that the conjunction of the two is the hallmark of executive control in children. Diamond's research has, however, also indicated that an overarching ability to coordinate EF components follows its own developmental trajectory (Diamond, 2001; Diamond, Prevor, Callender, & Druin, 1997). This makes her developmental model similar to the "unity and diversity" model of EF proposed by Miyake et al. (2000) for adults. According to Garon et al. (2008), this ability to coordinate EF components, supposedly achieved through the development of integrative attentional functions, is what drives the growing integration and complexity of EF components.

Operational Issues

A scientist's dream would of course be to be able to continue discussing *constructs* throughout a text, without worrying about issues pertaining to operationalization. However, because such utopian ideas rarely (if ever) exist in reality, we must in this case first discuss the choice of the WM task used in Study I and III, that is, backward version of the Digit Span subtest of the

WISC-III (Wechsler, 1992). There are heated exchanges over the issue of whether this task actually assesses WM or merely measures processes similar to those measured by the forward version of the task (i.e., short-term storage) (e.g., Engle et al., 1999; Oberauer, Süss, Schulze, Wilhelm, & Wittmann, 2000). However, the arguments for this task being particularly attention demanding and therefore a WM task, *in children*, are rather strong (Elliott, Smith, & McCulloch, 1997; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Rosen & Engle, 1997; also see, Hutton & Towse, 2001). This is because the systematic reordering of items may not be automatized in children to the same extent as in adults, and may therefore entail more executive demands in children. This argument is supported by theoretical propositions made by Engle and Kane (2004). We can also find support for the more executive demands that backward reordering of recalled items impose on the task in Study I. We found that there was a considerable amount of variance in the backward version of the Digit Span task that did not overlap with the forward version. This residual variance, in turn, related significantly to both crystallized and fluid intelligence, which illustrated a pattern of findings that theoretically fits well with that often described for the executive WM components. We would also like to repeat that neither of the WM tasks used in the present studies was intended to capture the entire integrating function of executive attention, but rather aspects related to the maintenance of information during simultaneous cognitive processing. Consequently, our conclusions regarding the executive WM component do not go beyond the aspects of storing and processing information.

Second, we need to acknowledge some limitations, along with some clear advantages, that accompany the use of WM residuals as a measure of executive WM processes. This procedure has a sound base in the "theoretical equation" presented by Engle and Kane (2004): WM = STM + executive WM processes. Further, the executive WM component has been commonly evaluated as WM after controlling for short-term memory (Colom, Abad et al., 2005; Colom, Flores-Mendoza et al., 2005; Engle et al., 1999; Kane et al., 2004), which is equivalent to using WM residuals. The additional advantage of using residuals rather than mere control for STM is that the residuals can be used on their own, in cases when involving STM would complicate matters (such as in Study II). However, there are also some concerns about using this kind of indirect assessment. Because there are still uncertainties as to what exactly is measured by STM tasks, as well as what specific processes are tapped by WM tasks, we might be left with even greater uncertainties regarding what is left in WM variance after removing STM variance. In other words, it is important to realize the limitations of not being able to assess the executive WM processes in a direct manner. I wish to stress the very high priority I feel future studies should give to achieving an empirically based understanding of WM residuals, as such an understanding would greatly extend present theoretical accounts (Engle & Kane, 2004).

In the context of operational issues, the confounding role of sustained attention in cognitive measurement should also be considered. Although any cognitive measure may be confounded by a number of factors, sustained attention may be one of the more conceptually relevant constructs confounding cognitive measurement. I have argued that all cognitive tasks that extend over some time should tax the sustained attention system to some extent, in addition to the intended phenomenon. To capture any ability as purely as possible, one therefore needs to eliminate the variance accounted for by this attention function. In Study I, we provided support for the notion that sustained attention only explains a small part of the relations of intelligence with STM, the executive WM component, and interference control. This further strengthens the extant evidence for the strong role of these functions in intellectual functioning.

Interpretations in Relation to Structure

The knowledge gained about the function of the WM system can also shed light on how we should view the structure of this system. The notion of a unitary WM system has for some time given way to a system of several distinguishable components (e.g., Baddeley's multicomponent model of WM; Baddeley, 2007). To cite Miyake and Shah (1999), "We hereby declare the bankruptcy of a completely unitary view of working memory" (p. 449). In other words, remaining questions concern which components are implicated in this system, with one of the more critical specifications pertaining to the domain-specificity or generality of the executive WM component. By showing that verbal and visuospatial executive WM processes are independent, in terms of their relations to intellectual functioning, we have provided support for the domain-specific view of WM. According to this view, not only the storage processes but also the executive WM processes are suggested to rely on separate resources for the verbal and visuospatial domain. We have moreover suggested that this domain-specificity may already be in place in school-aged children. Based on the attentional view of the executive WM processes, this would mean that there are at least some aspects of the system responsible for attentional control over to-be-remembered material that are separate for verbal and visuospatial information, respectively. This finding is in line with some neuroimaging as well as correlational studies in adulthood (Fletcher & Henson, 2001; Shah & Miyake, 1996). A domain-specific view is in contrast to a view according to which these attentional processes are used freely, without regard to the specific content of the material, as suggested by domain-general perspectives (Baddeley, 2007; Engle & Kane, 2004).

Relevant to the issue of domain-specificity is whether executive WM components can be distinguished from storage components in children. The present thesis has provided data suggesting that there is a substantial difference in what is measured by STM and WM tasks, and that this difference (i.e., the WM residuals) is relevant to complex cognition. In short – it seems as if short-term storage and executive WM processes can be told apart in school-aged children. In fact, this appears to be true in both the verbal and visuospatial domain, and by finding this result both in Study I and Study II, which used different STM and WM tasks, further support is given to this distinction. Our results are in line with accumulating evidence from factor-analytic data on children, adolescents, as well as adults indicating that there is an important difference between STM and WM tasks (Alloway, Gathercole, & Pickering, 2006; Alloway, Gathercole, Willis, & Adams, 2004; Conway et al., 2002; Engle et al., 1999; Gathercole et al., 2004), and this "difference" in turn is often interpreted as reflecting some kind of attention-demanding or executive features.

In emphasizing the separability of the WM components, I do not mean to oversimplify matters by suggesting that they are not related to each other. The components must be viewed in light of the system that they consitute, and they are, without a doubt, interrelated. Our data do not allow us to draw any firm conclusions about whether these interrelations indicate a general resource being tapped by all components or a system with separate but co-functioning parts (cf., the discussion of *g*/intelligence, p. 6-7 and 54-55 in this thesis). We therefore leave this question open. The important message to keep in mind from this section is that verbal and visuospatial short-term storage and, more importantly also, verbal and visuospatial executive WM processes appear to rely on at least partly separate resources in children.

The Nature of Intelligence in Children

By finding evidence that several different WM components, as well as inhibitory interference control, sustained attention, and processing speed, constitute relevant, independent aspects of intellectual functioning, this thesis supports a multifactorial perspective on intelligence (e.g., Detterman, 2000; Thurstone, 1938). Providing such data on children is particularly important, in that studies of this kind on children have been very scarce. Although we might not hold as strong a belief in pure *independence* of the functions as Detterman does (e.g., 2000), our results are clearly incompatible with the perspective of intelligence as a global moderator (*g*) – a *single* characteristic of a person that affects performance on nearly everything (Spearman, 1927; also see, Jensen, 1998). Spearman further believed in the existential reality of *g* as an entity, and maintained that specific abilities were distributed to a person randomly, but that *g* was what caused reliable individual differences in performance.

Detterman (1982, 1986, 1987, 2000), being a proponent of the multicomponent view of intelligence, views intelligence as a complex system of independent but interrelated parts, where some parts of the system are more important than others. Each person can be thought of as having a set of independent abilities related to each other by a set of weights specifying each ability's relation to other abilities in the performance of a particular task or test. According to Detterman, *g* arises from a person's independent abilities together with this set of weights. The analogy of a multiple regression analysis could be given here. The predictor variables have different weights in the prediction of the outcome variable. If a variable with a high predictive weight changes slightly, the outcome variable changes dramatically. Similarly, in the multicomponential context of intelligence, if a function having a high weight were to be impaired, devastating effects could be the result, whereas impairment of a low-weight function in the system might go unnoticed.

From this point of view, WM, because it is strongly implicated in intelligence in the literature, could be thought of as having a high weight in deciding level of task performance. However, it does not appear to be the only ability contributing. We have shown that, in addition to WM components, the capacity to inhibit interfering concurrent stimuli, the ability to uphold attentional resources, and the speed with which cognitive processes in general are executed also appear to have significant weights in intellectual functioning. From a purely multicomponential point of view, WM and the other functions can be regarded as *constituting highly relevant aspects of* intelligence, rather than as *being highly relevant to* intelligence.

Multifactorial views on intelligence have previously received criticism for the proposed independent parts being intercorrelated, which would suggest the presence of some kind of general factor (e.g., Cattell, 1971). This was also the case in Study I; the specific functions tested against intelligence were independently related to intelligence, but they also shared common variance, as indicated by the difference between the total explained variance in intelligence and the sum of the unique contributions of the predictors. Comments about factor intercorrelations indicating a general factor have previously been met by pointing out the problem of relying on correlations in this issue. However, in that case it would seem difficult, nearly impossible, to find support for a general intelligence factor, even if such a factor only complemented independent factors. We therefore choose to leave open the possibility that the shared variance among predictors in the explanation of intelligence may imply that some common underlying resource supplements the independent cognitive functions. Thus, our results could tentatively also be said to be in line with a hierarchical model of intelligence, such as that proposed by Carroll (1993).

The present findings on intelligence must be viewed in light of the particular intelligence tests that were used. We used the Verbal Comprehension factor-index from WISC-III (Study I and III; Wechsler, 1992) as a measure of crystallized intelligence, and to assess fluid intelligence, we used the Perceptual Organization factor-index from WISC-III (Study I and III) and Raven's Progressive Matrices (Study II; Raven et al., 1977). Raven's Progressive Matrices is considered a hallmark measure of fluid intellectual abilities (e.g., Carpenter, Just, & Shell, 1990; Raven, Court, & Raven, 1988) Also, the WISC factor-indexes are proposed to tap crystallized and fluid intelligence, respectively (Wechsler, 1992). Although the fluid aspects of WISC performance have been criticized for not being so fluid after all (e.g., Blair, 2006), it should be noted that the theory of fluid and crystallized intelligence actually emerged from the heterogeneity of subtests that comprised this particular test battery (Cattell, 1963). We, however, acknowledge the fact that the subtests in WISC-III leave room for improvement regarding degree of fluidity. Such a development has indeed been made in its most recent revision (WISC-IV; Wechsler, 2003)

As crucial as higher-order cognitive functioning is in normal individuals, just as devastating are impairments in these functions, impairments that can accompany brain damage or neuropsychiatric disorders. We will now turn to a discussion of the last issue examined here – that of the implication of intellectual deficits in children with ADHD.

Intellectual Deficits in Children with ADHD

Study III approached the issue of intellectual weaknesses in children with ADHD. First, we have added to the growing evidence for the existence of intellectual deficits in these children (e.g., Fraizer et al., 2004). The children with ADHD showed deficits relative to children with no psychiatric diagnosis and children with a psychiatric diagnosis other than ADHD, which extends previous research by showing that these deficits are specific to the ADHD diagnosis rather than a general correlate of any neuropsychiatric diagnosis.

Second, and more importantly, the present findings have increased our understanding of what these deficits imply about ADHD, by specifying that they are not mediated by impairment in several central EF-related functions and non-executive functions. In other words, intellectual deficits tell us something about the cognitive nature of ADHD, in addition to what is told by deficient EF. Third, these intellectual deficits appeared to be related to both ADHD symptom domains. I will start by considering the implication of the intellectual deficits found beyond deficient specific functions. This discussion will be followed by conclusions that can be drawn regarding the consequences of controlling for intelligence in ADHD research.

One crucial question to discuss is what kind of information intellectual deficits carry, and how gaining a better understanding of this information can enhance our general understanding of ADHD. It should first be mentioned that some aspects of the intellectual deficits were accounted for by combining deficits in the functions WM, inhibition, sustained attention, STM, and processing speed. Given the significant overlap between these functions and intelligence evidenced in Study I, as well as similar findings from previous studies (e.g., Ackerman et al., 2005; Dempster, 1991), this result was not surprising. Before I continue to discuss the implication of intellectual weaknesses in ADHD, I need to allude to the important differences found between the two intelligence types.

The results described above of intellectual deficits that go beyond deficits in specific cognitive functions refer to what was found for fluid intelligence. For crystallized intelligence, on the other hand, the initial deficits found in children with ADHD were mediated by these children's malfunctioning EF-related functions and non-executive functions. So, in other words, deficits in crystallized intelligence do not appear to give us any information about ADHD in addition to that gained through the studied EF-related functions and non-executive functions. This difference in findings between fluid and crystallized intelligence demonstrates the value of studying these intelligence types separately, particularly in studies of ADHD.

The question of what *additional* information could be gained from studying intelligence in children with ADHD, thus, only regards fluid intelligence. One possible interpretation of the deficit in fluid intelligence found beyond specific functions is that, although we have argued against a single general intelligence factor (Spearman, 1927), it may well be possible that multiple independent factors are supplemented by an overarching general factor, controlling the "intelligence system". This possibility has been outlined above, when discussing the fact that there was common variance between the specific functions in the explanation of intelligence (see, p. 55-56 in this thesis). Proponents of either of the extreme sides of the "*g*"-"pure independent components" controversy have argued that their view is more parsimonious and should therefore be more favorable (see e.g., Detterman, 1982). However, it could be argued that an explanation in terms of *either* the multifactorial *or* the *g* account might be too parsimonious, and may therefore lose explanatory value. Instead, an interpretation incorporating both independence of separate factors *and* a general determining control function may be the most parsimonious explanation that still has sufficient explanatory value. Such a structural organization is similar to that suggested for the EF components, in terms of their unity and diversity (Miyake et al., 2000).

The proposed general resource should be implicated in the integration of multiple cognitive components into a tight system; it should hold the function of binding and integrating, among other factors, EF components. This description is strikingly similar to the theoretically proposed function of executive attention processes, which are suggested to be the shared core of EF components (e.g., Baddeley, 2007; Garon et al., 2008; Miyake et al., 2000). In this view, the common heart of the EF system would thus appear to go beyond this system to also integrating an even larger system of cognitive control – the "intelligence system". The normal development of these attentional mechanisms has been suggested to set the stage for EF components to develop their complexity (Garon et al., 2008). Therefore, these executive attentional deficits, which we propose that children with ADHD have, may be thought of as underlying these children's weaknesses in separate EF components. It may be the case that these attentionally integrative functions are too intricate to assess using any *single* task. Miyake and colleagues (e.g., 2000) have indeed suggested that these functions are tapped by the common variance among EF component variables. Perhaps a factor score from a test battery of fluid intelligence could be viewed as corresponding to the common variance among EF component tasks, and this multi-task approach may be the best means we have today of tapping a larger extent of the integrating function of the executive attention processes in a more direct manner.

Our interpretation that the fluid deficits in children with ADHD represent attentionally integrative processes, tied to the prefrontal cortex, fits nicely with findings from cognitive neuroscience. These findings suggest that intelligence is best viewed as a distributed property of multiple interconnected cortical regions, which may have a prefrontal "hub" (Shaw, 2007).

Although the model of the "executive relatives" (see, p. 13-15 in this thesis) used as a basis for the interpretations made here is theoretically based, it clearly needs more empirical studying. This is particularly true of the broad hypothetical concept of executive attention. Testing models where executive attention mediates the correlations between different EF components would be a first step, as it would pave the way for testing more specific predictions about the integrative nature of these processes (see e.g., Garon et al., 2008). One important but extremely challenging mission for future research is to construct and validate tasks or batteries of tasks that directly assess processes whose function is to integrate a cognitive system.

A clinical implication of our interpretation of intellectual deficits in children with ADHD regards the development of EF training programs, such as that presented by Klingberg and colleagues (e.g., 2005). As executive attentional processes are suggested to underlie the development of the EF components (Garon et al., 2008), intervention programs involving training of *individual EF components*, such as WM, may not be targeting the central processes that bring about EF deficits. Greater effects could perhaps be expected if the cognitive training instead aimed at the *underlying* deficit in attentional functions. However, more valid ways to train these functions will have to wait until we have reached a better understanding of them, including the development of tasks that directly measures these complex functions. As yet, we do not know if executive attentional functions are even possible to train, but the positive evidence regarding training of individual EF components (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002; Thorell, Lindqvist, Bergman, Bohlin, & Klingberg, in press) lend support to this possibility. It should also be mentioned that the positive effects of WM training appeared to transfer to intelligence tests in some studies (Klingberg et al., 2002, 2005).

Regardless of whether or not the "attentionally integrative capacity" interpretation of our findings receives further support in future research, some of our findings are nonetheless important. First, the fluid deficits found in addition to important specific cognitive deficits were similar in magnitude to those found for the central EF components and non-executive functions included in our study. This gives us a hint as to the relevance of the information that could be gained from studying fluid abilities in ADHD. Second, these fluid deficits were related to both ADHD symptom domains of inattention and hyperactivity/impulsivity.

The Role of Intelligence in ADHD Research

One general conclusion that could be drawn from the present data is that intelligence, without a doubt, deserves more attention in the ADHD literature than merely using it as a simple control variable. This phenomenon clearly holds the potential to give us important information that could help in unraveling the issues of cognitive impairments related to ADHD.

Information on the question of whether or not intelligence should be controlled for in ADHD research comes from both Study I and Study III. Study I showed that several different EF-related components as well as non-executive functions constituted relevant independent aspects of intelligence.

This information is crucial in the debate on controlling for intelligence. From this point of view, I would like to argue that just because a more specific and demarcated function (e.g., an EF component) is part of a larger system does not make this specific function less valid per se. Does it seem reasonable to control for the performance of the whole university when studying the achievements of one particular department? To state my opinion clearly, I believe that controlling for intelligence in ADHD research, at least in the study of EF, removes information that is highly relevant to the actual research questions (i.e., cognitive impairment in ADHD). The same arguments hold for both fluid and crystallized intelligence. It could even be argued that the EF aspects removed due to overlap with intelligence are among the "purest" EF variance, in that the possible confounding elements introduced by idiosyncratic task requirements should be minimized. This makes the case even worse.

Study III supports the notion that something really is removed regarding the contributions of EF components when we control for intelligence – there is indeed overlapping variance between ADHD, intelligence, and EF-related components, particularly for crystallized intelligence. Our findings further suggest that we should altogether move away from the notion of intellectual ability as a confounding phenomenon that needs to be partialled out. Rather, we should acknowledge its potential relevance in capturing supreme integrating attentional processes.

Some Take-Home Messages

To conclude my thesis, I would like to refer back to the major aim in the form of a question: In what way has the present thesis enhanced our understanding of human higher-order mental functioning? The thesis has provided data that can be interpreted to mean that mental processes supporting complex cognitive functioning are best viewed as representing a system of primarily independent parts that might be accompanied by an overarching common mechanism. The multiple components involve, but are surely not limited to, WM, interference control through inhibition, sustained attention, and processing speed. One of these functions, WM, can be further partitioned into domain-specific executive WM processes and domain-specific short-term storage processes, all of which constitute important aspects of higher-order cognitive functioning.

We have further learned that when one or several of these functions are compromised, this affects the overall functioning of the individual. However, what is more surprising is that deficits in fluid intelligence in children with ADHD may represent more than weaknesses in WM, inhibition, sustained attention, STM, and processing speed. This additional fluid deficit is tentatively interpreted as superior executive attention processes, hypothetically serving to integrate EF components into a system.

A coherent theory of human cognitive functioning necessitates more knowledge about a thus far relatively neglected part of the population: children. This makes the present studies a particularly valuable contribution to the research field. The modest contribution of the current thesis of course only constitutes a fraction of the work that is needed to reach stable conclusions regarding the issues studied here. I specifically appeal to future researchers to undertake the crucial issues of studying what is actually reflected in the variance in WM tasks that is not shared with STM tasks at different developmental levels. Further, an important task for future studies to take on is to explore the validity of our “attentionally integrative capacity” interpretation of fluid intellectual deficits in children with ADHD. Coming to an understanding of these issues would constitute a very important step toward a better comprehension of human higher-order mental processes in both normal and neuropsychiatric populations. Given that neuroscience methods have been suggested to have particular potential in distinguishing between perspectives on intelligence (Gray & Thompson, 2004), this cognitive research field needs to be complemented by more studies using methods such as neuroimaging and genetic analysis.

In sum, I believe that the current thesis has lived up to the expectations of the ultimate goal presented in the introduction: It has contributed to an enhanced understanding of higher-order cognitive functioning. It is now up to forthcoming research (including my own) to continue the battle with tasks and tests, with statistical procedures and experimental manipulations, so that some time in the future we can finally reach a fair consensus in our understanding.

Acknowledgements

First of all, I would like to express my deepest gratitude toward my supervisor, **Gunilla Bohlin**. You are a truly excellent researcher with many qualities worth striving for, which makes you an admirable person and a great role model for a young scientist like me. More or less every day for the past five years I have gathered material for this acknowledgement. You have *always* been there for discussions and guidance regardless of the subject. When I have encountered bumps along the road toward the goal of completing this thesis, a short meeting with you has almost always been enough to put me back on track. Our frequent theoretical discussions have always left me bubbling with energy to break new grounds. I will really miss that. You have in the best way possible prepared me for the world outside.

I would also like to thank my co-supervisor, **Ann-Margret Rydell**. You have always been open to answering and discussing scientific questions, whether regarding minor points on statistical regression residuals or major theoretical issues on the dimensionality of ADHD. Also, your Öland-heritage and eye for Norrland nature doesn't make you less likable!

I am also forever thankful to my dearest friends and colleagues, **Linda Forssman**, **Mari Fransson**, and **Sofia Lindqvist** for making my time here so pleasurable. It has been a true privilege and sheer joy to meet you guys every day. Linda, hold on to your amazing creativity, as well as your ability to step back and critically see the bigger picture of what is really important in scientific issues. Mari, you are a true "frisk fläkt" wherever you go. You are an incredible young scientist, with your never-ending strive to find real-life meaning in science, and conduct investigations that make a difference in people's lives. There should be more scientists like you out there. Sofia, no one can doubt your scientific skills (indeed, you had two published papers for your half-time seminar!). Sharing a room with you, I can only hope that some of your talent has rubbed off on me. You are a true friend and good listener, and your sense of Kalmar-humor leaves no one unaffected. In other words, how could I go wrong in such a scientifically as well as socially stimulating environment? You are my best friends. My time here would not have been the same without you.

I also want to thank **Lilianne Nyberg** for our interesting and pleasant collaboration. The fact that you persistently keep pursuing the impossible issue of studying the interaction between working memory and inhibition – with success, I should add – shows how great a researcher you really are. You must really love statistical interactions, huh?! You also happen to be a great person with a great laugh. I have always enjoyed our discussions, whether being of scientific or personal nature.

I would also like to thank our newest addition to the research group, **Sara Folke**. Your wonderful charisma lights up the dullest meeting, and it didn't take long to realize your great scientific potential. Go, PB's! Thank you, **Karin Brocki** and **Cecilia Wåhlstedt** for good friendship and collaboration.

Special thanks are also directed at **Astri J. Lundervold** at the University of Bergen, for generous cooperation, which has proved to be very fruitful as two of the papers in this thesis originate from our work together. I hope that our collaboration will continue in the future.

Last but not least, I am very grateful to my mother, **Christine,** and my father, **Curt**, who have always supported me whatever I wanted to do (I never became an airhostess, but maybe that's ok?). **Jonas**, how many times have I come to you with complaints about stupid reviewers, stupid articles, or stupid statistical formulas? Although not always having a clue as to what I was talking about and although not always agreeing with me, you have always been there to discuss these issues and make me realize that some (if not all) of these problems are not the end of the world. You have always been interested in my work, and I think that the meaning of executive functions actually stuck the tenth time I described it to you! You are the love of my life.

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