Working memory capacity and children's achievement in arithmetic and reading

van der Sluis, S.

Publication date
2005

Document Version
Final published version

Working memory capacity and children's achievement in arithmetic and reading

Printed by Print Partner Ipskamp, Enschede, the Netherlands

Working memory capacity and children’s achievement in arithmetic and reading

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. mr. P.F. van der Heijden
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Aula der Universiteit
op donderdag 27 januari, 2005, te 10.00 uur

door
Sophia van der Sluis
geboren te Edam

Promotor: Prof. dr. A. van der Leij

Copromotor: dr. P.F. de Jong

Faculteit der Maatschappij- en Gedragswetenschappen

Contents

1

Introduction

The working memory (WM) system is viewed as an elaborate mechanism that combines simple mnemonic functions with regulatory processes, also known as executive functions (EFs). These EFs are thought to be responsible for the organization, coordination, and control of cognitive processes during the performance of complex cognitive tasks (e.g., Lindsay, Tomazic, Levine, & Accardo, 1999; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). The WM system derives its significance from many studies, in which substantial correlations are reported between WM capacity and other cognitive abilities such as language comprehension (e.g., Daneman & Merikle, 1996), verbal ability (e.g., Cantor, Engle, & Hamilton, 1991), vocabulary (e.g., Gathercole & Pickering, 2000), arithmetic ability (e.g., Adams & Hitch, 1997; Fürst & Hitch, 2000; Geary, Hamson, & Hoard, 2000), and general fluid intelligence or problem solving ability (e.g., de Jong & Das-Smaal, 1995; Engle, Laughlin, Tuholski, & Conway, 1999; Kyllonen & Christal, 1990).

The most prominent, and now widely accepted, WM model was formulated by Baddeley and Hitch (1974). According to these authors, the working memory system comprises three components. Two subsidiary systems, the phonological loop and the visuo-spatial sketchpad, are responsible for the temporary storage of phonological, and visual-spatial information, respectively. In addition, a modality-free supervisory system, the Central Executive (CE), is responsible for actuating the two subsidiary systems, and for controlling, regulating, and monitoring cognitive processes (e.g., Baddeley & Logie, 1999).

The aim of all three empirical studies, collected in this thesis, was to study reading ability and arithmetic ability in relation to the functioning of the different components and subroutines of the WM system. One way to elucidate the relationships between reading, arithmetic, and WM capacity, is through differential studies. In such studies, various groups, which differ in reading and/or arithmetic ability, are compared with respect to the capacity on one or more of the WM components. This research design is employed in Chapter 2 and 3. In these studies, the functioning of different components of the WM system is compared in children with reading disabilities, children with arithmetic disabilities, and children with disabilities in both reading and arithmetic, and chronological age controls. The finding that groups perform comparably with respect to some components, but differently with respect to others, may be interpreted in support of the proposed fractionation of the WM system.

Another way to investigate the relations between the different WM components and reading and arithmetic is the use of confirmatory factor analysis (CFA) in non-clinical populations. This approach is employed in Chapter 4. In CFA, the hypothesized structure of a complex construct such as the WM system (or parts thereof) can be put to the test explicitly, and the individual relations between the WM components, and reading and arithmetic ability can be examined.

In the present chapter, some key concepts of the empirical studies in the chapters 2, 3, and 4 are introduced. Subsequently, the research questions are summarized, and an outline of this dissertation is presented.

Working memory

As mentioned, the WM system is thought to comprise three different components: the phonological loop, the visuo-spatial sketchpad, and the central executive. Recently, Baddeley (2000) proposed a fourth component, the episodic buffer. This component is supposed to be responsible for the multimodal integration of information from the two subsidiary systems, and long-term memory. However, this fourth component does not enjoy the general acceptance of the other three components. At present very little studies, including the ones presented in the following chapters, have taken this fourth component into account. The following sections are therefore confined to the widely accepted three-component WM model.

Phonological loop

The phonological loop can be considered analogous to the original short-term memory concept. This component is thought of as a system of limited capacity that is used for the temporal storage of phonological information. The phonological loop has been subdivided into a passive phonological store, and a phonological recapitulatory system, i.e., a rehearsal mechanism (Baddeley & Logie, 1999). Within the phonological store, information is represented and maintained in phonological code, and, to prevent decay, the rehearsal process serves to refresh these phonological representations (Baddeley & Logie, 1999). This fractionation allows for the explanation of experimental findings such as the similarity effect (i.e., phonological similarity between to-be-recalled items reduces span capacity), the word length effect (i.e., memory span is a function of the spoken length of to-be-recalled items), and the articulatory suppression effect (i.e., the continuous repetition of a (meaningless) phoneme reduces span capacity).

Phonological loop capacity is usually measured through simple span tasks, in which subjects are presented with a series of stimuli, usually digits or words, which have to be recalled in their order of presentation.

Visuo-spatial sketchpad

The visuo-spatial sketchpad (VSSP) has only recently become the focus of a concerted research effort. Although this subsidiary system has long been viewed as a unitary system, evidence gathered over the last decade suggests that this subsidiary system is characterized by a two sub-component structure (Pickering, 2001). Pickering discusses three different views on the fractionation of the VSSP. Although these views differ somewhat in their emphasis and terminology, they include the distinction between memory for 'static' visual information (i.e., color, form), and memory for 'dynamic' visual information (i.e., movement, direction).

This distinction can be recognized in the tasks used to measure the capacity of the VSSP. In 'static' VSSP tasks, subjects are required to recall patterns that were presented to them as a whole. In 'dynamic' tasks, visual information is presented serially, and subjects are required to recall place as well as order.

Central executive, and its subroutines

For a long time, the exact nature of the Central Executive (CE) remained unclear (e.g., Baddeley, 1996). At first, it was viewed as a unitary supervisory system that was involved in the simultaneous storage and processing of information, and served as the driving force of the WM system by activating and coordinating both subsidiary systems. Recently, however, so-called executive functions (EFs) have been proposed as subroutines of the CE (e.g., Baddeley, 1996; Miyake et al., 2000).

These EFs are considered responsible for organizing and monitoring the processing of information, and controlling and coordinating cognitive processes during the performance on complex cognitive tasks (Lindsay et al., 1999; Miyake et al., 2000). A wide variety of meta-cognitive processes have been considered to be executive in nature, such as planning, organized search, impulse control, goal directed behavior, set maintenance, flexible strategy employment, selective attention, attentional control, initiation of actions, inhibition, fluidity, and self-evaluation (e.g., Letho, Juujärvi, Kooistra, & Pulkkinen, 2003; Sikora, Haley, Edwards, & Butler, 2002; Wu, Anderson, &

Castiello, 2002). Baddeley (1996) proposed to narrow down this motley of executive abilities to four more general EFs: shifting, inhibition, updating, and dual task performance. The first three EFs are generally acknowledged as simple, lower level executive abilities. However, the status of dual-task performance as lower level EF is disputed (see for example, Miyake et al., 2000; Rabbitt, 1997). The studies in this thesis focus on the three undisputed EFs: inhibition, shifting, and updating.

Updating ability. Updating concerns the dynamic revision of the content of memory in light of new, relevant information, and the ability to store and process information simultaneously. As described above, CE capacity, or simply 'working memory capacity', was defined in a similar fashion before its fractionation. The EF updating can thus be considered analogous to the former unitary view on the CE in that it requires the actuation of the subsidiary systems.

Well-known measures of updating ability (also simply called WM tasks) are complex span tasks like Reading span (e.g., Daneman & Carpenter, 1980), Listening span (e.g., Siegel & Ryan, 1989), and Counting span (e.g., Case, Kurland, & Goldberg, 1982). In these tasks, subjects are presented with stimuli, which have to be transformed or manipulated before recall.

Inhibition. Several subtypes of inhibition have been distinguished (e.g., Friedman & Miyake, 2004; Nigg, 2000). In this thesis, the focus is on one subtype of inhibition, i.e., the ability to deliberately suppress dominant, automatic, or prepotent behavioral responses in favor of responses that are more relevant to the task at hand.

Tasks like the Stroop task are used to measure this type of inhibitory ability. In this task, subjects are presented with color words printed in incongruent ink colors (e.g., 'red' printed in yellow). Subjects are required to name the ink color, and to suppress the automatic and dominant tendency to read the color-word.

Shifting. Shifting is defined as the ability to switch between sets, tasks, or strategies, i.e., the disengagement of an irrelevant task set, and the subsequent activation of a new, more appropriate one.

Shifting measures usually require subjects to perform a simple task according to certain rules, and they have to switch between the rules in response to an external cue.

Previous studies on WM, reading, and arithmetic

As stated above, substantial relations between the capacity of the WM system, and reading and arithmetic ability have been reported in various studies. With regard to reading, the phonological loop has been suggested to be involved in the reading process. For the early reader, the word decoding process is still laborious, because segments of words have to be memorized (i.e., storage) while remaining segments are decoded (i.e., processing) (e.g., de Jong, 1998; Siegel & Ryan, 1989). This requirement to store and process information simultaneously appeals to the CE, which is therefore thought to be involved particularly when reading ability is not yet fully automatized. There is little indication that the VSSP is involved in the reading process, although some have hypothesized that this visual component of the WM system is relevant for the development of a 'sight word vocabulary', i.e., the direct recognition of word forms and word images (e.g., Howes, Bigler, Lawson, & Burlingame, 1999). As yet, there is little evidence to support this hypothesis.

In the context of arithmetic, the WM system is thought to be involved in the memorization of numbers during the arithmetic process (phonological loop), the spatial representation of multi-digit problems (VSSP), and the initiating, directing, and monitoring of procedures in complex arithmetic problems (CE) (McLean & Hitch, 1999). In addition, Geary (1993, 2004) argued that the WM system plays a role in the development of long-term memory representations of basic arithmetic facts.

WM and learning disabilities

The involvement of the WM system in reading and arithmetic does not necessarily imply that the WM system is implicated in deficits in the acquisition of reading and arithmetic abilities. Several studies have addressed this particular issue, and groups characterized by reading disability (RD) or arithmetic disability (AD) have sometimes been found to perform more poorly on (working) memory tasks than controls (for reading: e.g., de Jong, 1998; Howes, Bigler, Lawson, & Burlingame, 1999; Howes, Bigler, Burlingame, & Lawson, 2003; Siegel & Ryan, 1989; Swanson, 1999; Swanson & Ashbaker, 2000; for arithmetic: e.g., Bull, Johnston & Roy, 1999; Hitch & McAuley, 1991; McLean & Hitch, 1999; Siegel & Ryan, 1989; Swanson, 1994). However, studies, in which the WM performance of groups with different subtypes of learning disabilities (LD) is addressed simultaneously, are rare. As a result, comparisons between different LD groups are based on comparisons over studies, rather than on direct comparisons. The accuracy of such comparisons depends heavily on the comparability of the tasks used to assess WM capacity, and on the criteria used to select children with LD. Due to these critical requirements, it remained unclear whether children with different LD subtypes are characterized by different WM deficits.

In addition, in many studies no explicit distinction is made between children with RD *with*, and children with RD *without* additional problems in arithmetic ability. This differentiation is especially important, as deficits in reading and arithmetic coincide more often than is to be expected based on the prevalence of specific deficits in reading or arithmetic alone (e.g., Geary, 1993). In order to unambiguously attribute group differences in performance, alternative explanations, such as an additional arithmetic related deficit, need to be precluded.

Furthermore, with regard to CE capacity, researchers have focused mainly on updating ability, i.e., the ability to store and process information simultaneously. Both inhibition and shifting ability have been studied with respect to RD (e.g., Everatt, Warner, Miles, & Thompson, 1997; Helland & Asbjørsen, 2000), or AD (e.g., Bull, Johnston & Roy, 1999; Bull & Scerif, 2001; Sikora, Haley, Edwards, & Butler, 2002), but to our knowledge no studies have been conducted, in which different LD subgroups are compared simultaneously with respect to these executive abilities.

In the two studies presented in Chapter 2, the functioning of the three main components of the WM system - the CE, the phonological loop capacity, and the VSSP - are examined and compared in samples of children with RD, children with AD, children with learning disabilities in both reading and arithmetic (RAD), and controls.

The study presented in Chapter 3 focuses on inhibition and shifting ability in children with different LD subtypes, and controls.

The structure of executive functioning

Miyake et al. (2000) studied the structure of executive functioning in adults, and found that the three EFs inhibition, shifting, and updating were indeed distinguishable as distinct, yet related, functions. The structure of executive functioning in children has been addressed through exploratory factor analysis (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Klenberg, Korkman, & Lahti-Nuuttila, 2001; Levin et al., 1991; Welsh, Pennington, & Groisser, 1991), but only a few studies have taken the distinction between inhibition, shifting, and updating as the point of departure in a confirmatory factor analysis. The two studies that did (Letho et al., 2003; Manly et al., 2001), have confirmed the distinction between these three EFs in children.

Unfortunately, the interpretation of these factorial solutions and their comparability over studies is thwarted by the use of 'impure', or complex EF tasks. Because EFs can not be measured directly, i.e., need a task context to become manifest, EF tasks inevitably appeal to additional, non-executive cognitive abilities such as verbal ability, motor speed, or visual-spatial ability. That is, EF tasks are always 'impure'. As a result, it has proven difficult to attribute performance on EF tasks to the absence or presence of specific executive capacities.

In both studies on executive functioning, presented in Chapters 3 and 4, this task impurity problem is addressed through the application of so-called control tasks. These control tasks are analogous to the executive tasks, except that they do not require executive ability (e.g., Denckla, 1996; Sergeant, Geurts, & Oosterlaan, 2002). In Chapter 3, the control tasks were mainly used to account for the possible differential influences of non-executive task demands on the performance on executive measures of children with, and without LD on executive measures. In Chapter 4, the structure of executive functioning is studied in a non-clinical sample of children. Here, control tasks were included in confirmatory factor analysis, which allowed us to distinguish non-executive common variance from executive common variance. Subsequently, the relations of both non-executive, and executive task demands with reading ability and arithmetic ability could be examined.

Research questions and Outline of this thesis

The studies presented in the Chapters 2 and 3 focus on WM capacity in the context of learning disabilities. In both studies, different LD subgroups participate simultaneously, alongside a chronological age control group.

The questions central to these studies are:

- Are learning disabilities related to deficits in one or more of the components or subroutines of the WM system?
- If so, are different learning disabled subgroups characterized by different, distinguishable WM profiles?

Chapter 2 focuses on the functioning of the three main components of the WM system: the central executive, the phonological loop, and the VSSP. In Chapter 3, two executive subroutines of the central executive, i.e., inhibition and shifting, are examined.

The study in Chapter 4 focuses on the structure of executive functioning in a non-clinical sample of children. In addition, the relations between the individual EFs and reading ability, arithmetic ability, and reasoning ability are explored.

The questions central to this chapter are:

- Can the EFs inhibition, shifting and updating be distinguished as separate factors in children?
- If so, how are these EFs related to reading ability, arithmetic ability, and reasoning ability?

The results of these three empirical studies are discussed in Chapter 5, and in that final chapter some recommendations are made for future research.

2

Working memory in Dutch children with reading and arithmetic related learning deficits [1]

The aim of the present studies was to examine working memory performance in children with various subtypes of learning disabilities in a Dutch population. Performance of children with reading disabilities (RD) was compared to that of children with arithmetic disabilities (AD), children with reading and arithmetic disabilities (RAD), and chronological age controls (CA). Measures covered the phonological loop, the visuo-spatial sketchpad, and the central executive. In both studies, the children with RD showed no working memory deficits whatsoever. Children with AD showed a single impairment on the task tapping working memory for dynamic visual information. Children with RAD performed poorly only on the Digit span Backward task. The failure to replicate the expected working memory deficits in children with reading related disabilities is discussed.

[1] van der Sluis, S., van der Leij, A., & de Jong, P.F.
In press: *Journal of Learning Disabilities*

Introduction

One way to elucidate the relation between working memory capacity and higher order cognitive abilities has been to study working memory performance in children with learning disabilities. Such studies address the question whether (specific) learning disabilities coincide with (specific) working memory deficits. More explicitly, the goal of these studies is to elucidate the nature of specific learning deficits by studying their correlates. Over the years, many of these inquiries have demonstrated that children with learning disabilities related to reading (RD) have lower working memory capacity than average readers. Specifically, children with RD have greater difficulty with the simultaneous processing and storage of information than non-reading disabled peers (e.g., Siegel & Ryan, 1989; Swanson, 1993, 1994, 1999; De Jong, 1998; Swanson & Sachse-Lee, 2001). Similarly, studies have also found working memory deficits in children with a specific disability in arithmetic (AD) (e.g., Hitch & McAuley, 1991; Bull & Johnston, 1997; Bull, Johnston, & Roy, 1999; Siegel & Ryan, 1989; Geary, Brown, & Samanayake, 1991; Geary, Hoard, & Hampson, 1999; Geary, Hamson, & Hoard, 2000). However, several authors have expressed concerns about the selection of participants in studies on learning disabilities (e.g., McLean & Hitch, 1999; Bull & Johnston, 1997; Rourke, 1993; Rourke & Del Dotto, 1994). Also, studies, in which groups with different subtypes of learning disabilities are compared simultaneously, are rare. The use of different tests and different criteria for being considered disabled has complicated the comparison of results obtained in different studies. The question therefore remains whether working memory capacity differs between these subgroups. The aim of the present studies is to examine and compare working memory capacity in carefully selected samples of children with RD, children with AD, children with disabilities in both reading and arithmetic (RAD), and controls.

The significance of the working memory construct arises from the strong relations that have consistently been found between working memory capacity and higher cognitive abilities, such as language comprehension and reading (e.g., Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Swanson, 1999), verbal ability (e.g., Cantor, Engle, & Hamilton, 1991), vocabulary (e.g., Gathercole & Pickering, 2000), arithmetic ability (e.g., Adams & Hitch, 1997; De Rammelaere, Stuyven, & Vandierendonck, 1999; Fürst & Hitch, 2000; Geary, Hamson, & Hoard, 2000; Hecht, 2002; Lemaire, Abdi, & Fayol, 1996; Logie, Gilhooly, & Wynn, 1994; Noël, Désert, Aubrun, & Seron, 2001) and general fluid intelligence or problem solving ability (e.g., de Jong & Das-Smaal, 1995; Engle, Laughlin, Tuholski, & Conway, 1999; Henry, 2001; Kyllonen & Christal, 1990). Working memory therefore seems to be an important correlate of cognitive capacity in general. Before we discuss the relation between working memory and academic skills like reading and arithmetic in more detail, we briefly elaborate on the working memory concept itself.

Unlike short-term memory (STM), which is considered a system of limited capacity for temporal storage of information only, working memory is regarded as a more elaborate mechanism that combines both storage and processing of information (e.g., Engle et al., 1999; Swanson, 1994). According to the most prominent working memory model (Baddeley & Hitch, 1974), working memory comprises of three subsystems. At the core of the model is the Central Executive (CE), a supervisory system responsible for control, regulation and monitoring of complex cognitive processes. In addition, the phonological loop and the visuo-spatial sketchpad (VSSP), two specialized slave systems, are used for the storage of verbal and visual/spatial information, respectively (e.g., Baddeley & Logie, 1999). The VSSP is sometimes subdivided into a part responsible for the storage of static visual information, i.e., information about form and color, and a part responsible for the storage of dynamic visual information, i.e., information about motion and direction (see Pickering, 2001, for a comprehensive review). Tasks tapping the VSSP capacity can be subdivided accordingly, and we will refer to those as 'static' and 'dynamic' tasks throughout the paper.

Phonological loop capacity is usually measured by simple span tasks, like digit span and span for words or non-words. In these tasks, subjects are presented with series of (non-) words or digits, and are required to repeat these in the order of presentation.

Apart from co-ordinating the functioning of the two subsidiary systems, the Central Executive (CE) is considered a limited capacity system that regulates the processes that are associated with working memory. These processes include the simultaneous storage and processing of information, or the ability to manipulate and revise the content of memory in light of new and relevant information (Baddeley, 1996). Well-known measures of CE functioning are complex span tasks like Digit span Backward, Reading span (e.g., Daneman & Carpenter, 1980), Listening span (e.g., Siegel & Ryan, 1989), and Counting span (e.g., Case, Kurland, & Goldberg, 1982). In these tasks, the stimuli, which have to be remembered, are not simply presented to the subjects, but have to be transformed before recall, or need to be established in another task.

Understandably, studies on working memory capacity in children with RD have mainly focused on the phonological component of the working memory system: the phonological loop. The phonological loop is supposed to play an important role in language acquisition (Baddeley, Gathercole, & Papagno, 1998). Because of its general co-ordinating function, attention has been devoted to the CE as well. Theoretically, a relation between reading ability and CE-functioning, as measured by complex span tasks, seems plausible, particularly in the stage when reading ability is not fully automatized. For the early reader, the word decoding process is still a chore, because segments of words or sentences have to be memorized while remaining segments are decoded. A relation between working memory capacity and reading is therefore expected. Yet, from the involvement of working memory in the act of reading does not automatically follow that subjects with RD have impaired working memory. Several studies have however demonstrated that children with RD are characterized by poorer phonological loop capacity as well as poorer CE-capacity (e.g., de Jong, 1998; Howes, Bigler, Lawson, & Burlingame, 1999; Howes, Bigler, Burlingame, & Lawson, 2003; Siegel & Ryan, 1989; Swanson, 1999; Swanson & Ashbaker, 2000). For example, de Jong (1998) compared working memory capacity of 10-year old children with RD with the performance of chronological age controls (CA) and reading level controls (RL). Administering multiple working memory measures tapping different academic domains (e.g., reading, computation, and counting), de Jong reported poorer performance of the group with RD compared to the CA controls on simple span tasks as well as tasks that required the simultaneous storage and processing of information, i.e., CE tasks. However, no differences in working memory capacity were found between the group with RD and the RL controls, suggesting a developmental lag in working memory capacity.

The VSSP-capacity of children with RD has received less attention, although the VSSP has been suggested to be involved in the development of a 'sight word vocabulary', i.e., the direct recognition of word forms and word images (e.g., Howes et al., 1999). Studies that did address the VSSP-capacity in children with RD have sometimes reported poorer capacity on visuo-spatial tasks (e.g., Howes et al., 2003; Swanson, 1994; Swanson & Ashbaker, 2000). For example, Swanson and Ashbaker (2000) report that children with RD performed more poorly than CA controls, and even more poorly than RL controls, on working memory tasks, including tasks for visual working memory. Howes and colleagues (2003) administered a battery of 18 working memory tasks to children with RD, and CA and RL controls. Compared to controls, children with RD had lower composite scores, which represented serial memory, verbal learning, and visual-spatial memory. However, not all subgroups with RD performed more poorly than RL controls, and not all subgroups with RD displayed deficits in visual-spatial memory.

In the context of arithmetic, working memory is thought to play a role in the memorization of numbers during the arithmetic process (phonological loop), the spatial representation of multi-digit problems (VSSP), and the initiating, directing, and monitoring of procedures in complex arithmetic problems (CE, McLean & Hitch, 1999). In addition, Geary (1993) argued that working memory deficits could lead to failure to develop long-term memory representations of basic arithmetic facts. Studies of working memory capacity in children with arithmetic disabilities (AD) generally indicate that phonological loop capacity is within the normal range (Bull & Johnston, 1997; Geary, Hamson & Hoard, 2000). At the same time, evidence concerning the CE and VSSP capacity of children with AD is mixed. Some studies report that performance of children with AD is poorer than that of children without arithmetic deficits with respect to the CE and the VSSP (e.g., McLean & Hitch, 1999; Bull, Johnston & Roy, 1999; Siegel & Ryan, 1989; Swanson, 1994). For example, Siegel & Ryan (1989) reported poorer performance on the Counting span task, but average performance on a Reading span task. Subsequently, Hitch and McAuley (1991) argued that this poorer performance of children with AD on the Counting span task was due to slower counting and more limited digit span, and could therefore not be taken as indicative of poor CE-functioning. However, their finding of limited digit span capacity was itself contradicted by findings reported by Bull and Johnston (1997) and Geary, Hamson and Hoard (2000). These researchers did not find differences in simple digit span performance of children with AD and CA controls, once differences in reading ability were controlled for. McLean and Hitch (1999) presented children with and without AD with tasks appealing to the phonological loop, the VSSP, and the CE. Children with AD performed more poorly on the Corsi Blocks task, a dynamic VSSP task, and on 4 out of 5 CE tasks, including one measure that required both storage and processing of incoming information. However, since this measure also required arithmetic skills, poor performance on this task could not be readily attributed to poor working memory ability. In addition, Bull, Johnston and Roy (1999), once they controlled for differences in reading ability and IQ, failed to replicate the finding of poor Corsi Blocks performance in children with poor arithmetic skills.

Summarizing, studies on working memory in children with RD have repeatedly reported deficits in phonological loop capacity, and CE capacity. The VSSP capacity of children with RD has to date received little attention, but some studies report defected VSSP capacity as well. Evidence of working memory deficits in children with AD is mixed. Some, but not all, studies have reported deficient CE-functioning, poor digit span capacity, and poor memory for dynamic visual information.

In most aforementioned studies, the working memory capacity of one subgroup with learning disabilities is compared to that of age- or level-matched controls. Studies in which groups with different subtypes of learning disabilities are compared simultaneously, are rare (e.g., Siegel & Ryan, 1989; Swanson, 1994; Geary et al, 1999, 2000). At the same time, in many studies no explicit distinction is made between children with RD *with*, and children with RD *without* additional problems in arithmetic. Yet, the distinction between these two groups is important since deficits in reading and arithmetic tend to coincide (e.g., Geary, 1993). In studies on reading disabilities, often no information is provided about the arithmetic performance of the participants (e.g., De Jong, 1998; Howes and colleagues, 1999, 2003; Swanson and colleagues, 1999, 2000, 2001, 2003). These authors report working memory deficits in their samples with RD, but since no information was available on arithmetic ability it cannot be determined whether these children had specific reading related disabilities, or were more truly characterized by a double learning deficit. Siegel and Ryan (1989, 1988) also report working memory deficits in children with RD. However, the authors indicated that very few children with low reading scores had arithmetic scores within the normal range.

Only in three studies were subgroups with different learning disabilities both accurately and reliably identified, and rendered comparable to controls with respect to additional measures like IQ (by means of matching or analysis of covariance). These studies are Swanson (1994), and Geary and colleagues

(1999, 2000). However, these studies were limited to a small number of working memory tasks, and therefore did not utilize a comprehensive assessment of the working memory system.

It is thus as yet unclear whether children with different learning disabilities show a similar configuration of working memory deficits.

Study 1

The aim of the first study was to compare the working memory performance of children with RD with that of children with learning deficits in both reading and arithmetic (RAD), and with that of children who did not experience learning disabilities, i.e., chronological age controls (CA). We expected children with RD to perform more poorly than CA controls on tasks tapping the phonological loop and the CE, i.e., on simple and complex span tasks. In addition, although former studies have not resulted in a univocal view of the working memory deficits accompanying arithmetic disability, we expected children with RAD also to score less well on tasks requiring the memorization of dynamic visual information.

Method

Participants. Parental consent was obtained for 252 children from grade 4 and 5 of 7 different schools in the region of Haarlem (the Netherlands). All children were screened with standardized tests for non-verbal reasoning ability, reading ability, and arithmetic ability. On the basis of these measures we selected 18 children with RD (11 boys, 7 girls), 15 children with RAD (6 boys, 9 girls), and 24 CA controls (11 boys, 13 girls). Of these 57 children, 48 attended schools for regular education (24 CA, 23 RD, and 7 RAD), and 9 children attended schools for special education (1 RD, and 8 RAD). Twenty-four children attended grade 4 (8 CA, 10 RD, and 6 RAD); 33 children attended grade 5 (16 CA, 8 RD, and 9 RAD). Descriptive statistics of the three groups are in Table 1.

For children to be admitted to the study, non-verbal intelligence scores had to be above the 35th percentile. To be considered reading disabled, children had to display a lag of at least 13 (instructional) months in technical reading ability (note that there are 10 instructional months in 1 school year). Children were considered doubly disabled if they displayed an additional lag of at least 13 (instructional) months on arithmetic ability.

Table 1 shows that, on average, the group with RAD had a reading grade of 2;3 and an arithmetic grade of 2;2, signifying a 2 year discrepancy between their expected achievement level, as based on their grade (4;4), and their actual achievement level. For the group with RD, the mean reading grade (2;5) but not the mean arithmetic grade (4;2) was well below their actual grade (4;2). Note that the arithmetic ability of the CA controls was on average up to standard (arithmetic grade 4;8, actual grade 4;4), but their reading ability was above the expected level (5;6).

The Raven Progressive Matrices (Raven, Court and Raven, 1979) was used as an indication of non-verbal intelligence. The Raven consists of sixty series of patterns that have to be completed with a pattern chosen from a set of answer options. Completion of this test took no more than 45 minutes.

Table 1
Characteristics of the chronological age controls (CA, n = 24), the group with reading disabilities (RD, n = 18), and the group with reading and arithmetic disabilities (RAD, n = 15) in Study 1

	CA		RD		RAD	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age (in months)	129.42	7.05	127.89	7.84	129.80	9.44
Grade	4;5	5	4;2	5	4;4	5
OMRT (raw scores)	77.00	5.81	48.00	11.03	44.80	11.46
Reading Grade	5;6	8	2;5	7	2;3	7
ATT (raw scores)	37.82	4.67	35.13	5.83	23.04	6.63
Arithmetic Grade	4;8	8	4;2	10	2;2	8
Non-Verbal Reasoning (norm scores)	111.73	10.53	114.65	10.79	101.33	6.30

Note. OMRT = One Minute Reading Test: raw scores are number of words read correctly in one minute. ATT = Arithmetic Tempo Test: raw scores are mean number of arithmetic problems completed correctly within three minutes. Grade represents the mean number of years and months of completed instruction. Reading Grade and Arithmetic Grade represent the grade in which that group’s reading/arithmetic level is normally reached. For example, a mean Reading Grade of 2;3 means that the group has on average reached a reading level that average readers generally reach after 2 years and 3 months of instruction.

Raven non-verbal reasoning norm scores are based on the 1986 American standardization sample. The percentile scores as given by the manual were translated to standard IQ scores (M = 100, sd = 15).

The Dutch One-Minute-Reading-Test (OMRT, Brus & Voeten, 1995) was used as a measure of technical reading ability, or oral reading fluency. This test consists of a list of 116 unrelated words. Subjects are instructed to read aloud as many words as possible in one minute without making errors. The test score was the number of words read correctly in one minute.

The Arithmetic-Tempo-Test (ATT, de Vos, 1992) was used as a measure for arithmetic ability. Like the OMRT, this is a speeded test. The ATT consists of three subtests. The first subtest requires addition, the second subtraction, and the third multiplication. Each subtest consists of 50 problems of increasing difficulty. About the first 20 problems of each subtest cover so-called arithmetic facts. For each subtest, children were instructed to solve as many problems as possible in three minutes. The average of the scores on the three subtests was used as an overall score.

Both the OMRT and the ATT are standardized tests that are frequently used in Dutch education as measures of early reading and arithmetic acquisition.

Participants were selected such that the three experimental groups did not differ in age ($F(2, 54) < 1$, *ns*). Also, the distribution of boys and girls over the three groups could be considered equal ($\chi^2(2) = 1.64$, *ns*), as well as the distribution over grades 4 and 5 ($\chi^2(2) = 2.12$, *ns*). Scores for reading ability and arithmetic ability were submitted to separate ANOVA's to verify whether the groups were adequately matched, and adequately differentiated. The groups differed significantly with respect to reading ability ($F(2, 54) = 136.90$, $p < .001$, $\eta_p{}^2 = .84$). Post hoc Tukey tests revealed that reading ability did not differ between the group with RD and the group with RAD ($p > .10$), but both groups had noticeably poorer reading ability than the CA controls (both *p*'s < .001). Likewise, an overall effect was found for arithmetic ability ($F(2, 54) = 39.41$, $p < .001$, $\eta_p{}^2 = .59$). Post hoc Tukey tests showed that arithmetic ability did not differ between the CA controls and the group with RD ($p > .10$), but the group with RAD had noticeably poorer arithmetic ability than the CA controls and group with RD (both *p*'s < .001). Furthermore, an overall effect was found for non-verbal intelligence ($F(2, 54) = 8.44$, $p < .01$, $\eta_p{}^2 = .24$). Post hoc Tukey tests showed that the CA controls and group with RD did not differ with respect to non-verbal intelligence ($p > .10$), but the non-verbal reasoning performance of the group with RAD was significantly poorer than that of the other two groups (both *p*'s < .01). These results suggest that the desired matching and differentiation of the groups was achieved with respect to reading and arithmetic ability. In addition, group differences in non-verbal intelligence will have to be accommodated in subsequent analyses, as the groups differed with respect to this variable.

Tasks. The Digit Span Forward task from the Dutch edition of the WISC-R (de Bruyn et al., 1986) was used to assess phonological loop capacity. Digit Span Forward is a simple span task, in which the experimenter reads aloud a list of digits at the rate of one digit per second. At the end of each list, subjects are asked to repeat the digits in order of presentation. The WISC-R Digit Span Forward does not include example items. The digit span task consists of seven series of two lists of the same length. The forward version starts with lists of three digits. The test is terminated when subjects fail to perform correctly on two lists of the same length. The test score was the total number of correct answers before termination.

Two complex span tasks were used to assess CE-capacity: Digit Span Backward, and Listening span. Digit Span Backward, also derived from the Dutch WISC-R (de Bruyn et al., 1986), is considered a complex span task, because subjects are required to recall the list of digits *in reversed order*. One practice item is presented to make sure that participants understand the reversal requirement. The backward version starts with lists of two digits. The test is terminated when subjects fail to answer correctly on two lists of the same length. The total number of correct answers before termination is used as test score.

The Listening span task was based on the listening span task designed by Siegel and Ryan (Siegel & Ryan, 1989). In this task, the experimenter read aloud sets of short sentences in which the final word was missing. For example, 'Apples are green and bananas are ___'. Subjects were instructed to complete the sentences. When all sentences in a set had been read and completed by the subject, the subject was required to repeat the words they used in completing the sentences in the right order. The response was considered correct if the subject repeated the supplied words in the right order, regardless of whether the completing word was correct within the sentence. The sentences were chosen such that the word required to complete each sentence was obvious. The test consisted of 11 sets of increasing difficulty. The test started of with two sets of two sentences, followed by three sets of three, four, and five sentences, respectively. Two practice sets were presented to make sure that the children understood the task. Testing was terminated when a subject failed to recall correctly two sets at a given difficulty level. The total number of sets answered correctly before termination was used as the test score.

The tasks used to assess visuo-spatial working memory were based on two matrices tasks that were developed by Pickering, Gathercole, Hall, and Lloyd (2001). Both tasks required subjects to recall patterns of black and white blocks that were presented on a computer screen. In order to get an indication of memory for static information as well as memory for spatial information, i.e., movement, Pickering and colleagues designed a static and a dynamic version of the matrices task. The patterns in the present study were constructed using a random number generator; i.e., series of random numbers determined the location and, in case of the dynamic task, the sequence of the patterns. All patterns and sequences were the same for all participants.

The Matrices Static task consisted of a series of matrices (see Figure 1 for an example) in which half of the cells were white, and the other half black. The patterns were presented on a computer monitor for 2 seconds. Subjects were instructed to look carefully at the pattern, and to remember the location of the black blocks. After 2 seconds, the screen went blank for half a second, whereupon an empty matrix of the same size was presented. Subjects were then required to point out the location of the target blocks. The experimenter used the computer mouse to fill the indicated blocks and subjects were asked to confirm the pattern before the next test item was presented. If the pattern was not as the participant intended, the experimenter changed the pattern until it was. Item difficulty was increased by adding one white and one black cell to the matrix every four trials. The test started with the presentation of four matrices with four cells. Testing was terminated when the subject failed to recall two or more items correctly at a given difficulty level. The test score was the total number of items answered correctly before the cut-off criterion was reached. Two practice items were administered, and the test was not started until the experimenter had ascertained that the child understood the task.

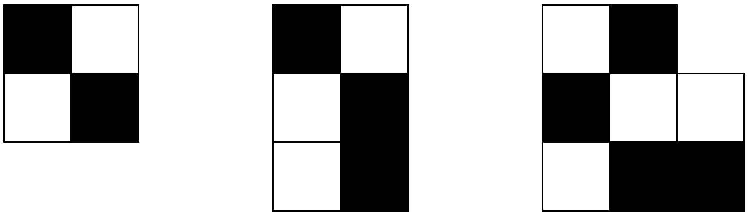

Figure 1. Three example patterns for the Matrices static task.

In the Matrices Dynamic task, subjects were presented with empty matrices in which half of the blocks sequentially flashed 'on' and 'off' for half a second, i.e., turned from white to black and to white again (see Figure 2 for an example). Then, after the screen had gone blank for half a second, a blank matrix appeared and subjects were asked to recall the location of the blocks that had changed color *in the right order* by pointing at the cells of the empty matrix. The experimenter used the computer mouse to select the target blocks in the order indicated by the subject. Again, the subject was asked to confirm the pattern and the order before the next item was presented. As in the static matrices task, the first four items consisted of matrices with four cells. Again, item difficulty was increased by adding two cells to the matrix every four trials. The same criterion for termination of the task was applied, and the test score was again the total number of items answered correctly before the cut-off criterion was reached. Again, two practice items were administered and testing was not started until the experimenter had ascertained that the child understood the task.

Both computerized tasks were presented on a Dell Intel Pentium III 800 Mhz desktop computer.

Procedure. The Raven and the ATT were administered in groups, whereas the OMRT was administered individually. The three screening tests were administered on the same day. The children were tested individually for working memory. The working memory tasks were spread over three separate sessions within a period of two weeks. In each session, one or two working memory tasks were administered (as well as other tasks that will not be reported on here). To prevent order effects, order of presentation of the working memory tasks was counterbalanced across participants. Digits Span Forward was the exception as this task always preceded Digit Span Backward. The experimenters were graduate students who were trained prior to testing.

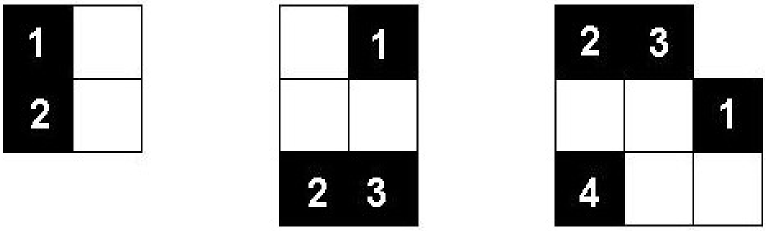

Figure 2. Three example patterns for the Matrices dynamic task (the numbers in the cells denote the order in which the cells flashed on and off).

Results

Means and standard deviations on all tasks for the three groups are presented in Table 2.

The tasks were analyzed per component of the working memory system by way of (multivariate) analysis of variance. Significant univariate tests were further investigated by means of Tukey pairwise comparisons. Note that the significance level alpha is set 'experimentwise' for the Tukey multiple comparisons, so the probability of committing a Type I error is .05 during the course of testing *all* pairs of means (Zar, 1999). As a result, the significance level is not much inflated in spite of to the number of contrasts.

To be certain that any differences found between the groups were due solely to the relevant learning disabilities, analyses of covariance were also carried out, to control for the differences between the groups in general intelligence.

Phonological loop. A one-way ANOVA was carried out comparing the three groups (CA, RD, and RAD) with respect to their scores on the Digit span Forward task. The main effect for Group was not significant ($F(2, 54) = 1.83$, *ns*). Children with learning disabilities did not perform more poorly than CA controls on this simple span task. These results were confirmed when differences in general intelligence were taken into account in an ANCOVA ($F(2,53) < 1$, *ns*).

Table 2
Means and standard deviations for all memory tasks for the chronological age controls (CA, n = 24), the group with reading disabilities (RD, n = 18), and the group with reading and arithmetic disabilities (RAD, n = 15) in Study 1

	CA		RD		RAD	
	M	*SD*	*M*	*SD*	*M*	*SD*
DF	5.89[a]	1.42	6.33[a]	1.81	5.27[a]	1.58
DB	4.88[a]	1.26	4.78[a]	1.66	3.60[b]	.63
LS	3.83[a]	1.61	3.50[a]	1.86	2.73[b]	1.39
MS	22.00[a]	2.47	22.50[a]	4.50	21.20[a]	2.54
MD	13.58[a]	2.22	14.67[a]	1.19	12.00[b]	2.46

Note. Scores with the same index can be considered equal. DF = Digit span Forward; DB = Digit span Backward; LS = Listening span; MS = Matrices Static; MD = Matrices Dynamic. All scores represent number of items answered correctly.

Visuo-spatial working memory. The scores on the two tasks tapping VSSP functioning, i.e., Matrices static and Matrices dynamic, were entered into a Multivariate Analysis of Variance (MANOVA) with experimental group as fixed factor. The multivariate main effect for Group proved significant ($F(4,108) = 2.59$, $p < .05$, $\eta_p^2 = .09$). Univariate tests showed that the groups did not differ with regard to performance on the Matrices static ($F(2,54) < 1$, *ns*), but they performed significantly different on the Matrices dynamic task ($F(2,54) = 5.64$, $p < .01$, $\eta_p^2 = .17$). Contrasts showed that the group with RD did not differ in memory for dynamic visual information from the CA controls ($p > .10$). However, the performance of the group with RAD was slightly poorer than that of CA controls ($p = .10$), and significantly poorer than that of the group with RD ($p < .01$).

However, when differences in general intelligence were controlled for in a MANCOVA, the multivariate main effect for Group was no longer significant ($F(4,106) = 1.58$, *ns*). Univariate tests were inspected anyway, since we wished to examine the effects that had proven significant in the previous analyses. To prevent an increase of the probability of committing a Type I error, a Bonferroni correction was carried out. Consequently, the univariate effects were tested against an alpha of .025 rather than .05.

No significant univariate effect was found for Matrices static ($F(2,53) < 1$, *ns*), but the effect for the Matrices dynamic showed a trend ($F(2,53) = 3.32$, $p = .04$, $\eta_p^2 = .11$). Subsequent contrasts showed that dynamic visual memory scores of the group with RD and CA controls, and the group with RAD and CA controls did not differ ($p > .10$). However, the group with RAD still performed significantly more poorly than the group with RD ($p < .01$).

Central executive functioning. The scores on the two task assessing central executive functioning, i.e., Digit span Backward and Listening span, were entered into a MANOVA with Group as fixed factor. The multivariate main effect for Group proved significant ($F(4,108) = 2.81$, $p < .05$, $\eta_p^2 = .09$). The univariate effect was not significant for Listening span ($F(2,54) = 2.10$, *ns*), but it was for Digit span Backward ($F(2,54) = 5.11$, $p < .01$, $\eta_p^2 = .16$). Contrasts revealed that the group with RD performed as well as CA controls on Digit span Backward ($p > .10$), but the performance of the group with RAD was poorer than that of both the CA controls and the group with RD (for both tests, $p < .01$).

However, when the differences in general intelligence were accounted for in a MANCOVA, the multivariate main effect for Group was no longer significant ($F(4,106) = 1.76$, *ns*). Again, we nevertheless wished to study the univariate effects, and a Bonferroni correction was carried out to prevent chance findings.

The univariate test for Listening span was not significant ($F(2,53) < 1$, *ns*), but the univariate test for Digit span Backward still showed a trend ($F(2,53) = 3.18$, $p = .05$, $\eta_p^2 = .11$). Contrasts revealed that the group with RD performed as well as CA controls on Digit span Backward ($p > .10$), but the performance of the group with RAD was still slightly poorer than that of the CA controls ($p < .05$), and the group with RD ($p = .05$).

Discussion

Contrary to the fair number of studies that report working memory deficits in children with reading disabilities, in this study the children with only reading related learning disabilities showed no impairments in working memory capacity. That is, the working memory performance of the group with RD did not differ from that of CA controls on simple or complex phonological span tasks, or on tasks tapping visual memory for either static or dynamic information. Children who experienced deficits in both reading and arithmetic, however, showed poorer performance than controls on Digit span Backward, and slightly poorer performance on the Matrices dynamic task. However, when differences in general intelligence were taken into account, only the effect for Digit span Backward remained. The small effect for Matrices dynamic seems therefore attributable to differences in general intelligence, rather than to the presence of learning deficits in both reading and arithmetic. The group with RD outperformed the group with RAD on Matrices dynamic and Digit span Backward. When differences in general intelligence were accounted for, only the difference for Matrices dynamic remained. Because memory for dynamic visual information did not differ between the group with RAD and the CA controls, it seems most accurate to interpret the difference between the two groups with learning disabilities as a confirmation of the conclusion that a sole disability in reading is not associated with impaired VSSP capacity. At the same time, it cannot be established from the present findings whether the problems that the group with RAD displays with regard to the Digit span Backward task, are related to the simultaneous presence of learning disabilities in both reading and arithmetic, or solely to their arithmetic disability.

As we noted before, in many of the studies that report working memory deficits in children with RD, either no information was provided on their arithmetic ability, or the participants with RD were characterized by additional poor arithmetic skills. At this point, it is important to acknowledge the possibility that the group with RAD in Study 1, and not the group with RD, was most like the groups with reading related disabilities in former studies. Still, when general intelligence was taken into account, only the difference on the Digit span Backward task proved robust. Because many studies have reported findings that are not in line with the current results, a replication of the study was called for.

Study 2

In Study 2, a group with specific arithmetic related disabilities (AD) was included in addition to a group with specific reading related disabilities (RD), a group with learning disabilities related to both reading and arithmetic (RAD), and chronological age-controls (CA). Inclusion of the group with AD enabled us to investigate whether working memory deficits as found in the group with RAD, could best be described as the sum of working memory deficits found in children with a single learning disability, or as resulting from the combined presence, or interaction, of disabilities in both reading and arithmetic. This possible interaction can only be descried when the working memory performance of children with a single (RD, AD), and double (RAD) disability are compared within one study. Furthermore, to clarify the relation between intelligence and working memory capacity, more careful matching of the groups on a measure of general intelligence was desirable. Therefore, all groups in Study 2 were matched on general IQ, and in all groups, mean IQ was within the normal range. Children from grade 4 and 5 had to display a deficiency of at least 15 months in reading, arithmetic, or both, to be considered disabled. Besides, the reading and arithmetic skills of the control group had to be within the normal range.

Method

Participants. Parental consent was obtained for 477 children from grades 4 and 5 of 10 different schools situated in the regions of Haarlem and Amsterdam (Netherlands). As in Study 1, all these children were screened on standardized measures of reasoning ability, reading ability, and arithmetic ability. Out of the sample of 477 children, we selected 25 children with RD (13 boys, 12 girls), 17 children with AD (4 boys, 13 girls), 16 children with RAD (8 boys, 8 girls), and 18 CA controls (9 boys, 9 girls). Of the 76 children, 6 attended a school for special education (3 AD, 3 RAD). All other children attended schools for regular education.

An overview of the characteristics of the four groups is presented in Table 3. Note that the mean reading grade of the groups with RD and RAD (2;3 and 2;1 for RD and RAD respectively) was approximately 2 years below their actual grade (4;2). Likewise, the mean arithmetic grade of the groups with AD and RAD (2;1 and 2;0 for AD and RAD respectively) was approximately 2 years below their actual grade. The reading and arithmetic grades of the CA control group (4;3 and 4;4 respectively) were up to standard.

As in Study 1, the OMRT and the ATT were used to screen the children for technical reading ability and arithmetic ability. Because some studies on specific arithmetic disabled children have reported somewhat impaired visual-spatial or non-verbal (reasoning) ability (e.g., Rourke, 1993; Share, Moffitt, & Silva, 1988; Strang & Rourke, 1983), the Raven did not seem an appropriate test for selection. It was therefore replaced by a verbal reasoning test to assess general reasoning capacity.

The subtest Verbal Analogies of the RAKIT, a Dutch intelligence test for children (Bleichrodt, Drenth, Zaal, & Resing, 1987), was administered to obtain a measure of verbal reasoning ability. The test consists of 30 forced choice items. Items were of the form 'A is to B as C is to ___', and children were asked to select the appropriate answer from four response options. Simple pictures illustrated all words in the analogy problems. Completion of the test took no more than 30 minutes, which proved to be sufficient for all children. Norm scores, ranging from 1 to 30, are available for children aged 8.10 to 11.02. Since some children in the sample were older than 11.02 years, norm scores were extrapolated. This procedure is appropriate since the test scores were exclusively used to prevent children with low reasoning ability to be admitted to the main study. Children with verbal reasoning scores below norm score 9 were excluded from the study, independently of their performance on the other screening tests.

Participants were selected such that the four groups were matched on age ($F(3, 72) = 1.25$, *ns*), and verbal reasoning ability ($F(3, 72) < 1$, *ns*). Also, the distribution of boys and girls over the groups and over grades 4 and 5 was equal ($\chi^2(3) = 4.01$, *ns* and $\chi^2(3) < 1$, *ns*, respectively). Note however that although the distribution of gender was not significantly different over the four groups, the distribution was somewhat unbalanced for the group with AD (4 boys, 13 girls).

ANOVA's were performed on the reading and arithmetic scores in order to verify that the groups were adequately matched and displayed the expected differences given the selection. An overall effect was found for technical reading ability ($F(3, 72) = 40.73$, $p < .001$, $\eta_p^2 = .63$). Post hoc Tukey HSD tests showed that the CA controls and the group with AD did not differ with respect to reading ability ($p > .10$), nor did the groups with RD and RAD ($p > .10$). However, both groups with RD and RAD performed significantly poorer on the technical reading test than the CA controls, and the group with AD ($p < .001$). Likewise, an overall effect was found for arithmetic ability ($F(3, 72) = 41.88$, *p*

< .001, η_p^2 = .64). Post hoc Tukey HSD tests showed that the CA controls and the group with RD did not differ significantly in arithmetic ability ($p > .10$), and neither did the groups with AD and RAD ($p > .10$). However, both groups with AD and RAD performed significantly poorer on the test for arithmetic ability than the CA controls, and the group with RD ($p < .001$). These results suggest that both the matching of the four groups on age and verbal reasoning, as well as the intended differentiation between the groups based on their reading and arithmetic ability, was achieved.

Table 3

Characteristics of the chronological age controls (CA, n = 18), the group with reading disabilities (RD, n = 25), the group with arithmetic disabilities (AD, n = 17), and group with reading and arithmetic disabilities (RAD, n = 16) in Study 2

	CA		RD		AD		RAD	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (months)	127.72	4.44	131.20	6.22	128.29	9.16	128.25	6.39
Grade	4;3	5	4;2	5	4;1	5	4;2	5
OMRT (raw scores)	69.17	2.55	47.08	7.25	65.88	11.51	42.87	11.82
Reading grade	4;3	4	2;3	5	4;2	14	2;1	7
ATT (raw scores)	35.44	2.54	34.55	4.38	22.63	5.98	21.96	6.47
Arithmetic grade	4;4	6	4;1	9	2;1	7	2;0	7
Verbal Reasoning (norm scores)	113.33	10.70	107.80	11.94	107.94	13.75	108.44	13.06

Note. OMRT = One Minute Reading Test: raw scores are number of words read correctly in one minute. ATT = Arithmetic Tempo Test: raw scores are mean number of arithmetic problems completed correctly within three minutes. Grade represents the mean number of years and months of completed instruction. Reading Grade and Arithmetic Grade represent the grade in which that group's reading/arithmetic level is normally reached. For example, a mean Reading Grade of 2;3 means that the group has on average reached a reading level that average readers generally reach after 2 years and 3 months of instruction.

The Rakit verbal reasoning scores are based on the 1984 Dutch standardization sample. The standardized scores as given by the manual (M = 15, sd = 5) are translated to standard IQ scores (M = 100, sd = 15).

Tasks. Phonological loop capacity was again measured by the Digit span Forward task as described in Study 1. Matrices Static and Matrices Dynamic, as described in Study 1, were used as indicators of VSSP-capacity. Three tests were used as measures for central executive capacity: the Digit span Backward task as described in Study 1, an adapted version of the Listening Span task as used in Study 1, and the Counting Span task.

The Counting span task is based on the test described by Case and colleagues (1982). Variations of this task have frequently been used in studies on working memory capacity in learning disabled children (e.g., Siegel & Ryan, 1989; Hitch & McAuley, 1991; de Jong, 1998; Bull & Scerif, 2001). We presented subjects with sets of cards with 34 yellow and green dots. The number of green dots varies between carts (ranging between 1 and 9). Children are instructed to count the green dots and to repeat the number of counted dots in the right order at the end of each set of cards. Every three sets, the length of a set increases by one, resulting in 15 sets increasing in length from 2 to 6 cards. The experimenter announces the increase in set length. Testing is terminated when a subject fails to recall two sets at a given difficulty level correctly. The number of items answered correctly before termination is used as the test score. To illustrate the basic principle of the task, the tester presents one example item, consisting of a set of two cards.

The Listening span task underwent a slight change in procedure in order to make the three CE-tasks as analogous as possible. In this adapted version, children are to judge the correctness of series of sentences that are read by the experimenter, memorize the last word of every sentence, and recall those words in the correct order at the end of each set. For example, the experimenter reads 'An elephant is a big animal' (right) and 'the color of grass is purple' (wrong), and the child recalls 'animal, purple'. This way, as in the tasks Counting span and Digit span Backward, children were required to remember the information that was (gradually) provided to them. The sentences used in this test are simple, short and obviously correct or incorrect. The test consists of 12 sets, increasing in length from 2 sentences to 5 sentences every 3 sets. Three practice items are administered before the actual testing starts. If subjects are unable to recall the last words of two sets of the same difficulty level, i.e., length, in the right order, testing is terminated. The number of correct answers before termination is used as test score.

Procedure. The verbal reasoning test and the ATT were administered group-wise, while the OMRT was administered individually. All three screening tests were administered on the same day. After selection, the participants were tested individually for working memory capacity. The experimental tests were divided over three separate sessions that took place over a period of three days to two weeks. Each testing session consisted of two working memory tasks (and one learning task not reported on here). Order of presentation of the experimental tasks was counterbalanced across participants, with the exception of Digit span Forward, which always preceded Digit span Backward. All tests were administered by graduate students, who were trained prior to testing.

Results

Means and standard deviations for all groups on all working memory tasks are presented in Table 4.

Table 4
Means and standard deviations for all memory tasks for the chronological age controls (CA, n = 18), the group with reading disabilities (RD, n = 25), the group with arithmetic disabilities (AD, n = 17) and the group with reading and arithmetic disabilities (RAD, n = 16) in Study 2

	CA		RD		AD		RAD	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
DF	5.67[a]	1.19	5.60[a]	1.68	5.64[a]	1.77	5.13[a]	1.54
DB	4.78[a]	1.26	4.52[a]	1.50	4.59[a]	1.33	3.38[b]	.72
LS	3.89[a]	1.57	4.16[a]	1.91	3.94[a]	1.68	3.31[a]	1.35
CS	9.11[a]	1.88	8.84[a]	2.29	9.00[a]	3.04	8.19[a]	3.31
MS	22.50[a]	3.24	23.60[a]	3.00	21.59[a]	4.37	22.25[a]	4.14
MD	14.28[a]	2.30	13.32[a]	2.12	12.18[b]	1.94	13.94[a]	2.17

Note. Scores with the same index can be considered equal. DF = Digit span Forward; DB = Digit span Backward; LS = Listening span; CS = Counting span; MS = Matrices Static; MD = Matrices Dynamic. All scores represent number of items answered correctly.

The tasks were analyzed per component of the working memory system. In order to find out whether the working memory deficits of the group with RAD could best be described as an additive combination of the deficits found in the groups with a single learning disablity, or as due to an interaction of arithmetic and reading disability, a 2 x 2 design was deemed necessary. Arithmetic ability (arithmetic disabled vs. non-arithmetic disabled) and Reading ability (reading disabled vs. non-reading disabled) were entered as fixed factors (see Willcutt et al., 2001, for a similar procedure). Significant main effects for Arithmetic ability and/or Reading ability, and significant interactions between the two were further investigated by means of Tukey contrasts in which the performance of the four groups was compared pair wise.

The phonological loop. The scores on the task tapping phonological loop performance, Digit span Forward, were submitted to a two-way ANOVA. None of the effects proved significant (Arithmetic ability, $F(1,72) < 1$, *ns*; Reading ability, $F(1,72) < 1$, *ns*; Arithmetic ability by Reading ability, $F(1,72) < 1$, *ns*). The performance on this simple span task was thus similar in all groups, irrespective of the presence of learning deficits.

Visuo-spatial sketchpad. The scores on the two tasks tapping VSSP capacity, i.e., Matrices static and Matrices dynamic, were entered into a two-way Multivariate Analysis of Variance (MANOVA). The multivariate main effect for Arithmetic ability was not significant ($F(2,71) = 1.35$, *ns*), and neither was the effect for Reading ability ($F(2,71) < 1$, *ns*). However, the Arithmetic ability by Reading ability interaction was significant ($F(2,71) = 5.15$, $p < .01$, $\eta_p^2 = .13$). Univariate tests showed that the interaction was only significant for Matrices dynamic ($F(1,72) = 7.47$, $p < .01$, $\eta_p^2 = .09$), and not for Matrices static ($F(1,72) < 1$, *ns*). Tukey multiple contrasts for the Matrices dynamic revealed that the scores of the group with RD, and the group with RAD did not differ significantly from each other ($t = .90$, *ns*) nor from the CA controls ($t = 1.45$, *ns*, and $t = .46$, *ns*, respectively). However, the group with AD performed significantly poorer than the CA controls ($t = 2.91$, $p < .05$). Scores of the group with AD did not differ significantly from those of the group with RD ($t = 1.70$, *ns*), but were slightly poorer than the scores of the group with RAD group ($t = 2.37$, $p = .09$).

Central executive. The scores of the three working memory tasks tapping central executive functioning, i.e. Digit span Backward, Listening span, and Counting span, were entered into a two-way MANOVA. The multivariate main effect for Arithmetic ability was not significant ($F(3,70) = 1.67$, *ns*). However, based on Study 1 an effect was expected for Digit span Backward, so univariate tests were inspected anyways. A Bonferroni correction was carried out to prevent chance findings, and the univariate effects were tested against an alpha of .02 rather than .05. The univariate tests showed that the performance of children with arithmetic disabilities did not differ from that of children without arithmetic disabilities on the Counting span or Listening span tasks ($F(1,72) < 1$, *ns*, and $F(1,72) = 1.04$, *ns* , respectively), but a trend was found for Digit span Backward ($F(1, 72) = 5.04$, $p = .03$, $\eta_p^2 = .07$). Similarly, the multivariate main effect for Reading ability was not significant ($F(3,70) = 2.08$, *ns*). Yet, the accompanying univariate test for Digit span Backward was significant ($F(1,72) = 6.13$, $p < .02$, $\eta_p^2 = .08$), whereas the univariate tests for Counting span and Listening span were not (for both, $F(1,72) < 1$, *ns*). The multivariate interaction between Arithmetic ability and Reading ability was not significant ($F(3,70) = 1.01$, *ns*), and neither were any of the accompanying univariate tests.

The effects for Digit span Backward were further investigated by means of Tukey multiple contrasts. These showed that the scores of the group with RD, and the group with AD did not differ significantly from each other, or from the scores of the CA controls (for all: $t < 1$, *ns*). However, the group with RAD scored significantly poorer than the group with RD ($t = 2.80$, $p < .05$), the group with AD ($t = 2.73$, $p < .05$), and the CA controls ($t = 3.20$, $p < .01$).

Discussion

As in Study 1, the children with RD in Study 2 performed as well as control children on all working memory tasks. The children with AD in Study 2 performed as well as controls on all tasks, except the Matrices dynamic. Their performance on this task did not differ significantly from that of the group with RD, but was slightly poorer than that of the group with RAD. In Study 1, the scores of the group RAD were lower than those of the CA controls and the group with RD on the Matrices dynamic task, but this effect disappeared for the greater part when differences in general intelligence were accounted for. In Study 2, the group with RAD performed as well as CA controls, and as the group with RD on the Matrices dynamic task. This confirms the conclusion of Study 1 that the somewhat poorer performance of the group with RAD in Study 1 could best be interpreted in terms of their lower general intelligence rather than in terms of their twofold learning-deficit.

Study 1 had shown that, once general intelligence was accounted for, the group with RAD performed as well as CA controls on all tasks except Digit span Backward. This was replicated in Study 2. When the four experimental groups were considered separately in Study 2, the Digit span Backward scores of the groups with RD and AD did not differ significantly from each other or those of CA controls. Although the performance of children with RD and AD was somewhat lower than that of CA controls, these differences were, when studied in isolation, too small to result in statistically significant effects. The Digit span Backward performance of the group with RAD, however, was significantly lower than that of all three other groups. The absence of effects for the singly disabled children alone, would lead one to conclude that children with RAD experience deficits that children with single learning disabilities do not display. Yet, given the absence of a significant Arithmetic by Reading interaction, this interpretation seems inaccurate. The problems that the group with RAD experience with regard to Digit span Backward might be best interpreted as an additive combination of the slight, and in itself not significant, problems that characterized the children with a single learning deficit.

General discussion

The finding that children with AD perform more poorly on a task requiring the memorization of dynamic visual information is consistent with the findings of McLean and Hitch (1999). These authors reported poorer performance of children with AD on the Corsi Block task, which is conceptually comparable to the dynamic version of the Matrices tasks used in this study. However, Bull and colleagues (Bull et al., 1999) did not find significant differences in Corsi Block scores between high and low mathematical ability groups. Yet, in the latter study, the low mathematical ability group was composed of the 50 % lowest scoring children of the research sample. McLean and Hitch employed a more stringent criterion, compounding their group with AD of children with raw scores in the bottom 25 % of the *norm* sample. Their selection procedure is more comparable to the selection procedures used in the present study because both procedures result in the selection of children with poor arithmetic ability compared to standardized norms, and not just in comparison with the other subjects in the research sample. The discrepancy between findings of Bull et al. (1999) on the one hand, and McLean & Hitch (1999) and the present study on the other, might therefore be explained by the different selection procedures, and, as a result, by the extent of the arithmetical deficit displayed by the groups with AD. The incompatibility of the results might also be due to the nature of the tests used to screen for arithmetic ability. The tests used in the present study and in the study of McLean and Hitch contained written computation problems only. The screening test used by Bull and colleagues in addition contained word problems, which were orally presented by the experimenter. These additional word problems might have resulted in the selection of children with arithmetic problems that are related to the comprehension of the arithmetical narrative rather than to the failure to master basic arithmetic skills.

It is as yet unclear how the relation between arithmetic related deficits and deficits in memory for spatial information should be interpreted. As noted earlier, the VSSP has been suggested to play a role in the mental representation of number and size, as well as in the written representation of multi-digit problems. However, studies on the nature of tasks such as the Corsi Block, like the study by Fischer (2001), report improved performance when the elements within an item were visible for a longer period (encoding time), and when the time between encoding and retrieving item information was extended (maintenance time). These findings suggest that sequential tasks, like the Corsi Block task and the Matrices dynamic, may not only appeal to visuo-spatial memory, but may also require speeded encoding, and controlled attention. The exact nature of the relation between arithmetic disability and working memory for spatial information thus merits further research.

The children with AD in Study 2 did not show any deficits on the tasks that required the simultaneous storage and processing of information, i.e., central executive functioning. These results are consistent with those of Bull and Johnston (1997), who also reported intact Counting span performance once differences in reading ability were controlled for. Siegel and Ryan (1989) reported intact performance on a Sentences span task, which is conceptually comparable to the Listening span task. Yet, their group with AD performed more poorly on the Counting span task. Hitch and McAuley (1991) argued that this poorer performance on the Counting span task was the result of a combination of slower counting speed and more limited phonological loop performance. Following this line of reasoning, the intact phonological loop capacity of the children with AD in our study might in turn account for their intact performance on the Counting span task.

The only working memory impairment that the group with RAD showed in the present studies concerned performance on the Digit span Backward task. This finding is in line with studies by Geary and colleagues (1999, 2000). These authors also reported normal performance of children with RD, AD, and RAD on the Digit span Forward, yet impaired performance of only the group with RAD on the Digit span Backward. However, the absence of a significant Arithmetic by Reading interaction in Study 2 suggests that this deficit of the children with RAD can best be interpreted as an addition of the very slight problems that characterize the children with either RD or AD, which in itself failed to reach significance. In other words, the performance of the groups with RD and AD on the Digit span Backward was somewhat poorer than the performance of the CA controls, but these differences were very small, and the present study lacked the power to identify them.

Since the group with RAD performed averagely on the Counting span and the Listening span task, the impairments found for Digit span Backward cannot be attributed to impaired central executive functioning per se. Again, which features of this task constitute the exact source of the problems that children with RAD experience, remains a question that should be addressed in future research.

Stephan et al. (2003) reported a clear dissociation between the hemispheres with regard to letter decision (left hemisphere) and visuo-spatial decisions (right hemisphere). Note that the specificity of the visuo-spatial memory deficit to the group with AD, and the more general deficit concerning the Digit span Backward task, which is rather verbal in nature, might indicate that the problems of the subgroups are hemisphere-specific.

Having stressed all findings that are in line with the results of former research, the issue remains why some of the working memory deficits concerning complex span tasks, as have been reported frequently in children with RD, were absent in the current studies. Below we discuss three possible explanations.

First, an important question in studies as the present concerns the extent to which the findings, or lack thereof, can be attributed to lenience of the applied selection criteria. Lenient selection criteria could result in the inclusion of pupils who are slow, but not actually disabled readers. However, close inspection of our samples with RD showed that two thirds of the participants performed in the lowest 5 % range of the norm sample, and the remaining one third in the lowest 10 % range. Such low positioning is generally denoted as ‘disabled’. In addition, when we repeated our analyses using only the 50 % poorest readers of the RD and RAD groups, and the 50 % poorest arithmeticians of the AD group (the matching on age and reasoning with the CA controls remained intact), the results turned out similar, apart from some small, and inconsistent effects for Listening span and Counting span for the group with RAD only. The more restricted group with RAD now performed slightly poorer than CA controls on Counting span in Study 2, and on Listening span in Study 1, but this latter effect was not replicated in Study 2. It therefore seems implausible that the expected working memory deficits were merely absent as a result of the applied inclusion criteria.

Second, children with reading related disabilities, who learn to read in transparent orthographies such as Dutch, are often characterized as very slow but accurate readers (e.g., de Jong & van der Leij, 2003; Yap & van der Leij, 1993; Wimmer, 1993; Wimmer, Mayringer, & Landerl, 2000). As a result, accuracy-based tests are not appropriate for the identification of subjects with dyslexia in transparent languages. We therefore used a screening test that measures word reading efficiency, or fluency. In studies on English-speaking subjects however, reading achievement is usually measured through accuracy-based tests. The grounds for selection of subjects with dyslexia thus differ between orthographies, and this may have repercussions on the composition of the groups with reading disabilities, and on the results. The OMRT is however a standardized measure that is frequently used in the Netherlands as screening instrument for reading disorders in educational as well as experimental settings (e.g., Bast & Reitsma, 1998; De Jong, 1998; Van Daal & Van der Leij, 1999; De Jong & Van der Leij, 2003; Wesseling & Reitsma, 2000). As, for example, De Jong (1998) did report working memory deficits in his group with RD, which was selected based on the same OMRT, the absence of working memory deficits in the present study cannot be entirely attributed to the fluency-, rather than accuracy-based selection.

Third, while working memory deficits are consistently being reported in studies on English-speaking children with RD, the effects are smaller, and less consistent in studies on children with RD who learn to read in more transparent orthographies. In German, for example, Wimmer, Mayringer, and Landerl (1998) did find the expected deficits, while Wimmer and Mayringer (2002) did not. When studies on children with RD who learn to read in a transparent orthography do report working memory deficits, the samples tend to comprise of young children (e.g., Holopainen et al., 2001; Lyytinen et al., 2001; Nopola-Hemmi et al., 2002; Porpodas, 1999; Wimmer, Mayringer, & Landerl, 1998). An international study by Seymour, Aro, and Erskine (2003) showed that accurate familiar word reading approaches mastery much more slowly in English than in other European orthographies. So children, who learn to read in transparent orthographies like German and Dutch, tend to read accurately at a much younger age than children who learn to read in deep orthographies like English. This is even so for children with dyslexia. It could therefore be hypothesized that reading achievement mediates the relation between working memory capacity and dyslexia. That is, as long as children with RD are not able to read accurately, their working memory capacity is poorer than that of chronological age controls. Yet, in a transparent orthography, reading, even slow reading, might stimulate the development of phonological abilities, and boost the performance on other phonology-oriented tasks, like simple and complex span tasks. Working memory capacity might therefore improve to age-appropriate levels under the influence of the act of reading itself. Such a recovery would be commensurable with the idea that children with RD experience a developmental lag in working memory capacity, rather than a persistent deficit (see Van Daal & Van der Leij, 1999, for a similar interpretation).

An analogous argumentation might hold for the relation between working memory capacity and arithmetic ability. Difficulties that children with AD experience with CE tasks like the Counting span task might decrease with age under the influence of (slowly) advancing arithmetic achievement. Longitudinal studies, in which the development of cognitive abilities like working memory capacity is repeatedly measured in children with dyslexia or dyscalculia, are required to confirm this developmental-lag hypothesis.

In sum, children with learning deficits in arithmetic and reading (RAD) performed more poorly than controls on a Digit span Backward task. The absence of an interaction between Arithmetic ability and Reading ability suggests that the Digit span Backward performance of children with RAD is best described as an additive combination of the, in itself small and insignificant, problems that children with single learning deficits experience. The problems of the group with RAD on this specific test are thus, although more prominent, not of a different nature than those of children with RD or AD. This inference can exclusively be made when subgroups with different disabilities are studied simultaneously, which demonstrates the advantage of a full research design as was employed in Study 2. Furthermore, children with a single arithmetic related learning deficit (AD) showed a specific impairment in working memory for dynamic visual information. The present results did not demonstrate any working memory deficits in children with a single reading disorder (RD). This is commensurable with the conclusion as reached by Pennington, Van Orden, Kirson, and Haith (1991) that working memory problems do not seem to be a primary deficit in dyslexia. Pennington stated that working memory problems might only characterize a subgroup of children with RD, and that the problems might not be persistent over time (p. 175). The mixed results of studies on the working memory capacity in children with RD underline the necessity to focus on the question of when, and under which circumstances, working memory deficits are detectable in subgroups with reading related disabilities.

3

Inhibition and shifting in children with learning deficits in arithmetic and reading [2]

The executive functions inhibition and shifting were studied in children with arithmetic disabilities (AD), children with reading disabilities (RD), children with disabilities in both reading and arithmetic (RAD), and controls. Measures involved the rapid naming of objects, digits, letters or quantities, with or without additional task requirements that reflected inhibition or shifting. Also the Making Trails task, reflecting shifting, was administered. For tasks without executive demands, children with AD were slower in the naming of digits and quantities, whereas children with RD were slower in the naming of digits and letters. For the executive tasks, children with AD as well as children with RAD were impaired on the Making Trails task, and on an object-naming task, which required both inhibition and shifting. Children with RD exhibited no problems in executive functioning. Furthermore, it was shown that children with RAD experienced the combination of problems that characterize children with a single learning deficit.

[2] van der Sluis, S., de Jong, P.F., & van der Leij, A.
Published in *Journal of Experimental Child Psychology, 87* (2004), 239-266

Introduction

Executive functions refer to the general purpose control mechanisms that modulate the operation of various cognitive subprocesses and thereby regulate the dynamics of human cognition (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). These cognitive control functions concern the monitoring, adaptation, and regulation of cognitive performance in reaction to changing (task) settings. A large body of evidence suggests that executive functioning is related to reasoning ability (e.g., Engle, Laughlin, Tuholski, & Conway, 1999; Kyllonen & Christal, 1990), and is involved in scholastic abilities such as reading (e.g., Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Gathercole & Pickering, 2000) and arithmetic (e.g., Adams & Hitch, 1997; De Rammeleare, Stuyven, & Vandierendocnk, 1999, 2001; Fürst & Hitch, 2000; Geary, Hamson, & Hoard, 2000; Noël, Désert, Aubrun, & Seron, 2001; Hecht, 2002). There is also evidence that children who experience difficulties in the acquisition of reading and arithmetic show deficits in executive functioning (e.g., Bull & Scerif, 2001; de Jong, 1998; Geary, Hoard, & Hamson, 1999; McLean & Hitch, 1999; Siegel & Ryan, 1988, 1989; Swanson, 1993; Swanson & Sachse-Lee, 2001). In the current study, we examined executive functioning in children with specific learning disabilities in either reading or arithmetic, as well as children with deficits in both reading and arithmetic, and compared their performance to the performance of chronological age controls with normal reading and arithmetic ability.

Executive functioning is often fractionated into a variety of distinct processes. The taxonomy proposed by Baddeley (1996) is most current. Baddeley distinguished four executive functions: inhibition, shifting, updating, and dual task performance. *Inhibition*, or suppression of dominant action tendencies in favor of more goal-appropriate behavior (Bull, Johnston, & Roy, 1999), is most often associated with executive functioning. Miyake et al. (2000) stressed the fact that inhibition can be either controlled and intended, or uncontrolled, as is the case in negative priming (longer reaction times [RT's] in response to recently ignored stimuli), and reactive inhibition (the tendency to suppress previous responses). These authors argued that suppression of responses qualifies as an executive function only if it is controlled and intentional. Another executive function distinguished by Baddeley is *shifting*, that is, the ability to shift attention or to shift between strategies or response sets. Shifting is characterized by the disengagement of an irrelevant task set or strategy, and the subsequent activation of a more appropriate one. The third cognitive function that is considered executive in nature is *updating*, which is the encoding and evaluation of incoming information for relevance to the task at hand, and subsequent revision of the information held in memory. This executive function is characterized by the dynamic manipulation of the content of memory. Information is not just stored passively; rather, it is revised in the light of new information. A final executive function according to Baddeley is *dual-task performance*. This function refers to the ability to co-ordinate performance on two tasks simultaneously. The main issue here is whether performance on a baseline task deteriorates due to the introduction of a second task that must be performed simultaneously.

Whether these four executive functions can be empirically distinguished or reflect a single unitary executive controller is still open to debate. Miyake et al. (2000) used confirmatory factor analysis to investigate whether frequently used executive function tasks (a) loaded on different factors (i.e., were distinguishable), and (b) loaded on a common executive functioning factor (i.e., were related). A model with three factors - inhibition, shifting and updating - was found to be tenable. No unique factor was found for dual-task performance. The three factors were moderately correlated, indicating a degree of communality. Miyake et al. concluded that both the communality and the specificity of the executive functions should be recognized. They also suggested, as did Barkley (1997) and others, that inhibition might be the key factor given that all executive functions involve inhibitory processes. For example, updating requires the discarding of irrelevant incoming information and the suppression of obsolete information. Both processes are a form of inhibition. Likewise, shifting requires the deactivation or suppression (i.e., inhibition) of an obsolete mental set in favor of a new one.

Notwithstanding an ongoing enquiry into which executive functions should be distinguished, many studies have considered one or more of these functions in the context of the acquisition of reading and arithmetic ability. For arithmetic ability, several studies have reported a relation with performance on complex span tasks, especially when these involved counting or numerical stimuli like digit span Backward and counting span (Bull & Scerif, 2001; Geary et al., 1999; McLean & Hitch, 1999; Siegel & Ryan, 1989; Wilson & Swanson, 2001). These complex span tasks may be viewed as indicators of updating ability. Several studies also demonstrated relations between arithmetic ability and performance on the Wisconsin Cart Sorting Task (WCST) and the Making Trails task, both measures of shifting capacity. In two correlational studies, Bull and colleagues (1999, 2001) found that the perseveration of response on the WCST was negatively correlated with arithmetical ability. That is, the lower the arithmetical ability, the more difficulty children displayed in shifting strategy or set. McLean and Hitch (1999) presented children of high and low arithmetical ability with three versions of the Making Trails task, which all required shifting. They found that children with arithmetic disabilities (AD) were slower than children with normal arithmetic ability on all versions of the task. Bull and Scerif (2001) examined the ability to inhibit responses in children with AD. They administered Stroop tasks, which required the naming of either color or quantity of stimuli under facilitating or interfering task conditions. The interference condition was assumed to provide an indication of the ability to inhibit prepotent or overlearned responses (i.e., the reading of words or digits) in favor of less automatized ones (i.e., the naming of ink color or number of digits). Only the naming of quantity in the interference condition appeared to be related to arithmetical ability. In conclusion, evidence suggests that children with AD have executive problems reflecting updating, as well as inhibition and shifting.

Executive functioning has also been studied in relation to reading ability (e.g., Daneman & Carpenter, 1980; Daneman, 1987). Several studies have reported executive deficits in children with reading disabilities (RD) (e.g., de Jong, 1998; Siegel & Ryan, 1988; Siegel & Ryan, 1989; Swanson, 1993; Swanson & Sachse-Lee, 2001). In most of these studies, complex span tasks, reflecting updating capacity, were used as measures of executive functioning. For example, Siegel and Ryan (1989) compared children with RD and normally-achieving peers on two complex span tasks; a listening span task, and a counting span task. Children with RD were found to perform more poorly on both tasks. In a similar study, de Jong (1998) presented children with RD with complex span tasks tapping updating ability in various academic domains: reading span, counting span, and computation span. Children with RD showed poorer performance on all complex span tasks compared to chronological age controls. However, their performance was not different from the performance of a group of younger children with the same reading age. These studies indicate that children with RD have deficits in updating which are independent of the task domain. Yet, as other aspects of executive functioning were not included in these studies, little is known about other executive functions of children with RD, such as inhibition and shifting.

The main aim of this study was to examine the relationship of CE functioning with reading and arithmetic disability. The study was confined to inhibition and shifting. In contrast to updating, these two executive functions have received little attention, especially with respect to reading ability. The study aimed to extend previous studies in two respects. First, most previous studies have focused on children with either arithmetic or reading disability. Studies in which both types of learning disability have been included are rare. Consequently, evidence that children with RD and children with AD show differences in CE functioning is based on different studies and not on a direct comparison of these groups. Comparisons over studies are possible, but depend heavily on the adequate selection of the disabled groups. Several authors have expressed concerns about the selection of participants in studies on learning disabilities (e.g., McLean & Hitch, 1999; Bull & Johnston, 1997; Rourke, 1993; Rourke & Del Dotto, 1994). Especially, the careful distinction between children with a single or double learning deficit is called for, because learning deficits in reading and arithmetic ability tend to coincide more often than would be expected by chance (Geary, 1993). Explicit distinction between children with a single and double learning deficit reduces the chance of inaccurate attribution of research results. In addition, little is known about the CE deficits of children with learning disabilities in both reading and arithmetic (RAD). Whether the CE deficits of children with RAD are simply the sum of the deficits found in children with single disabilities, or whether the CE deficits of this group resemble the deficits of one of the groups of a single disability, has hardly been examined. To address this issue, we included children with AD, children with RD, and children with RAD, in the current study.

A second extension concerned the measurement of executive functions. A difficulty in the measurement of these functions is the problem of task impurity (Denckla, 1994; Miyake et al., 2000). A pure measure of an executive function is hard to develop because executive functions always require a context to become manifest. Impaired performance on a single central executive task can therefore indicate a deficit in the particular CE function but might also reflect a failure to handle the additional non-executive task requirements. The measurement problem is aggravated because tasks meant to reflect different CE functions often also differ in many other respects. Accordingly, it is difficult to pinpoint a pattern of strengths and deficits on various tasks, to the absence or presence of specific CE deficits.

To overcome the problem of task impurity, performance on a particular CE task has been compared to the performance on a control task that is similar in every respect except the CE requirement (see e.g., Bull & Scerif, 2000; McLean & Hitch, 1999). By analyzing contrasting performance on pairs of tasks, the irrelevant but constant task requirements are ignored, while the relevant differences between the tasks are the unit of analysis. To our knowledge however, there has been no attempt to extend this principle to the measurement of various CE functions. In the present study, inhibition and shifting requirements were subsequently included in the same control task.

In this study, we used rapid naming as the control task (Denckla & Rudel, 1976)[3]. In such tasks, series of symbols have to be named as quickly as possible. Children with RD have repeatedly been found to be impaired in the rapid naming of letters, digits and, although less often, objects (see for a review Wolf & Bowers, 1999). This would imply that children with RD could already be distinguished from normal readers on the control task. For exploratory reasons, we included a variety of rapid naming tasks to examine the performance of children with AD on such tasks.

Variations in naming tasks have been used before to measure inhibition, such as the Stroop task (e.g., MacLeod, 1991) and the Quantity naming task (e.g., Bull & Scerif, 2001). For the present study, three new tasks were designed, which required the rapid naming of geometrical objects. In addition to object naming, the manipulated task conditions of these new tasks required inhibition, shifting, or both inhibition and shifting, respectively. In addition, for both executive factors a commonly used task was selected that matched the preferred task design. For Inhibition, the Quantity naming task as used by Bull and Scerif (2001) was suitable. For Shifting, no commonly used naming

[3] An additional reason for confining this study to the executive functions inhibition and shifting, is that updating cannot be readily measured within the rapid naming framework. That is, while inhibition and shifting can be indicated in terms of (decreased) naming speed, updating ability is indicated in terms of accuracy, or the number of items recalled correctly.

task was available. We therefore selected the Making Trails task (e.g., McLean & Hitch, 1999) because this task has the preferred task design with a baseline condition, and it has repeatedly proven its usefulness in the context of studies on arithmetic disability. Addition of these two well-known tasks provided the possibility to replicate effects found in earlier studies, thereby validating the comparability of this study to earlier studies.

Method

Participants

Parental consent was obtained for 469 children from grade 4 and 5 of 8 different schools in the region of Haarlem (the Netherlands). These children were screened on verbal reasoning ability, reading ability, and arithmetic ability. On the basis of these measures, four groups were composed: children with AD, children with RD, children with RAD, and chronological age controls (CA).

To be considered as disabled, children had to display a lag of at least 15 (instructional) months in technical reading ability or arithmetic ability (i.e., 1.5 school year). Children were considered doubly disabled if they displayed a lag of at least 15 (instructional) months in both areas. Furthermore, children with learning disabilities were only admitted to the study if their verbal reasoning scores were in the normal (i.e., age appropriate) range. At this point, it is important to note that we were only interested in learning disabilities that concerned the disability to master the *technical skill* of reading and arithmetic. That is, the focus was on children who had been unable to automatize the fundamentals of these skills. Chronological age controls were selected such that they matched the children with learning disabilities on age, and had scores within the normal range on all three screening tests.

From the 469 children that were screened, eighty-one children were selected to participate in the study. However, due to absence during the testing sessions (n=3, 2 CA, 1 AD) and outlying scores on two or more experimental tasks (n=4, 2 RD, 2 RAD)[4], data from only 74 children were included in further analysis. Of these 74 children, 18 were diagnosed with arithmetic disability (5 boys, 13 girls), 21 with reading disability (12 boys, 9 girls), and 16 with reading as well as arithmetic disability (8 boys, 8 girls). Nineteen children participated as chronological age controls (9 boys, 10 girls).

Participants were not screened for behavioral problems. However, in the Netherlands, the main reason for referral to special education is the combination of learning and behavioral problems. Only 6 of our participants (3 AD, 3 RAD) attended schools for special education. Given that 68 out of 74

[4] Scores were considered outlying if they were more than three standard deviations from the mean of the subgroup that the child was assigned to.

participants came from regular schools, it is unlikely that differences among groups are attributable to behavioral problems.

The verbal analogies subtest of the RAKIT, a Dutch intelligence test for children (Bleichrodt, Drenth, Zaal, & Resing, 1987), was used as a measure of verbal reasoning ability. The test consists of 30 multiple-choice items of the format 'A is to B as C is to …'. The children are asked to pick the right answer from a set of 4 options. Completion of this test took 30 minutes at most. The maximum score on the test was 30.

Word reading speed, or oral reading fluency, was assessed by the One Minute Reading Test (OMRT, Brus & Voeten, 1995). This test is a standard measure in Dutch education for early reading acquisition. The test consists of a list of 116 unrelated words. The children were instructed to read as many words as possible in one minute without making errors. The score on the test was the number of words read correctly in one minute.

The Arithmetic Tempo Test (ATT, de Vos, 1992) was used as a measure of arithmetic ability. Like the OMRT, this is a speeded test. The ATT consists of three subtests that only require elementary computations. The first subtest requires addition, the second subtraction, and the third multiplication. Thus, per subtest only one arithmetical operation is required. Each subtest consists of 50 items of increasing difficulty. About the first 20 problems cover arithmetic facts and thus mainly appeal to arithmetic fact retrieval. For each subtest, three minutes are allotted. The child is required to solve as many problems as possible in this time. The score on the test was the mean number of problems solved correctly over the three subtests.

Descriptive statistics of the four groups are presented in Table 1. Children were selected such that the four experimental groups were matched on verbal reasoning ability ($F(3, 70) < 1$, *ns*), and age ($F(3, 70) = 1.24$, *ns*). The distribution of the sexes over the groups was equal ($\chi^2(3) = 3.53$, *ns*), as well as the distribution of grades 4 and 5 over the groups ($\chi^2(3) = 5.20$, *ns*). ANOVA's were performed to ensure that the groups were either adequately matched or adequately differentiated with respect to reading and arithmetic ability. The groups differed significantly with respect to reading ability ($F(3, 70) = 73.79$, $p < .001$). Post hoc Tukey HSD tests revealed that the controls and the children with AD did not differ with respect to reading performance ($p > .10$). Similarly, children with RD, and children with RAD did not differ in this respect ($p > .10$). However, both groups with reading disabilities (RD and RAD) showed noticeably poorer reading performance than the groups without reading deficits (CA and AD; all *p*'s < .001). Likewise, the groups differed significantly with respect to arithmetic ability ($F(3, 70) = 91.58$, $p < .001$). Post hoc Tukey HSD tests showed that the controls and the children with RD did not differ with respect to arithmetic performance ($p > .10$), nor did the children with AD and the children with RAD ($p >. 10$). However, both groups with arithmetic disabilties (AD and RAD) showed noticeably poorer arithmetic performance than the groups without arithmetic deficits (CA and RD; all *p*'s < .001). These results suggest that both the intended matching, and the intended differentiation among the groups was achieved.

Table 1

Characteristics of the chronological age controls (CA, n = 19), the group with arithmetic disabilities (AD, n = 18), the group with reading disabilities (RD, n = 21), and the group with disabilities in both reading and arithmetic (RAD, n = 16)

	CA		AD		RD		RAD	
	M	SD	M	SD	M	SD	M	SD
Age (in months)	127.37[a]	4.59	128.72[a]	9.07	131.29[a]	6.38	128.25[a]	6.39
Grade	5;2 [a]	5	5;2 [a]	5	5;5 [a]	4	5;2 [a]	5
ATT (raw)	35.35	2.50	22.91	5.92	36.38	4.30	21.96	6.47
Arithmetic Grade	5;3 [a]	6	3;1 [b]	7	5;5 [a]	8	3;0 [b]	7
OMRT (raw)	69.05	2.53	67.00	12.13	51.19	5.44	42.87	11.82
Reading Grade	5;3 [a]	4	5;3 [a]	14	3;6 [b]	3	3;1 [b]	7
Verbal Reasoning	19.63 [a]	3.56	18.00 [a]	4.69	17.95 [a]	4.02	17.81 [a]	4.35

Note. Scores with the same index can be considered equal. OMRT = One Minute Reading Test; ATT = Arithmetic Tempo Test. Means for Grade, Reading Grade, and Arithmetic Grade should be interpreted as 'grade;months', with SD's as months.

Tasks

Four out of the five tasks used to measure executive functioning were based on the format of the regular automatized rapid naming task (Denckla & Rudel, 1976). Simple naming tasks were administered as control tasks. The scores on these regular tasks were compared to the scores on the manipulated naming tasks. Examples of all control tasks and executive tasks that required naming are in Figure 1.

All naming tasks consisted of a card of 40 stimuli divided over 5 rows, each containing 8 stimuli. In all tasks, (combinations of) 4 different stimuli were used, which alternated randomly but appeared approximately equally often. Children were instructed to name the stimuli as fast as they could without making errors. Instructions for all naming task variations were standardized. For all these tasks, the time required to name the 40 stimuli (rounded off to whole seconds) was used as the test score. All naming tasks were introduced by presenting an example of 2 rows, each containing 8 stimuli. The experimenter read the instructions aloud and illustrated the task by naming the first 4 stimuli of the example. Then the experimenter asked the child to finish the example. The examples were used to familiarize the children with the naming tasks and to ascertain that the children understood the task. In three cases, examples were presented twice because subjects were noticeably in doubt about the instructions.

Control tasks

Four control tasks were administered, which are denoted Letters, Digits, Objects, and Quantity. The Letters-task included the letters A, O, S and D; the Digits-task included the digits 1, 2, 3 and 4; and the Objects-task included the geometrical figures circle, square, triangle and diamond. The stimuli of the Quantity-task were arrays of small triangles varying in number from one to four. Digits, Objects, and Quantity were used as control tasks for the manipulated naming tasks. Although none of the manipulated naming tasks involved the naming of letters, the Letters-task was administered because reading disabled children are known to perform noticeably slower on tasks demanding the naming of letters and digits. The Letters-task was thus considered a check of the results we expect on the control tasks.

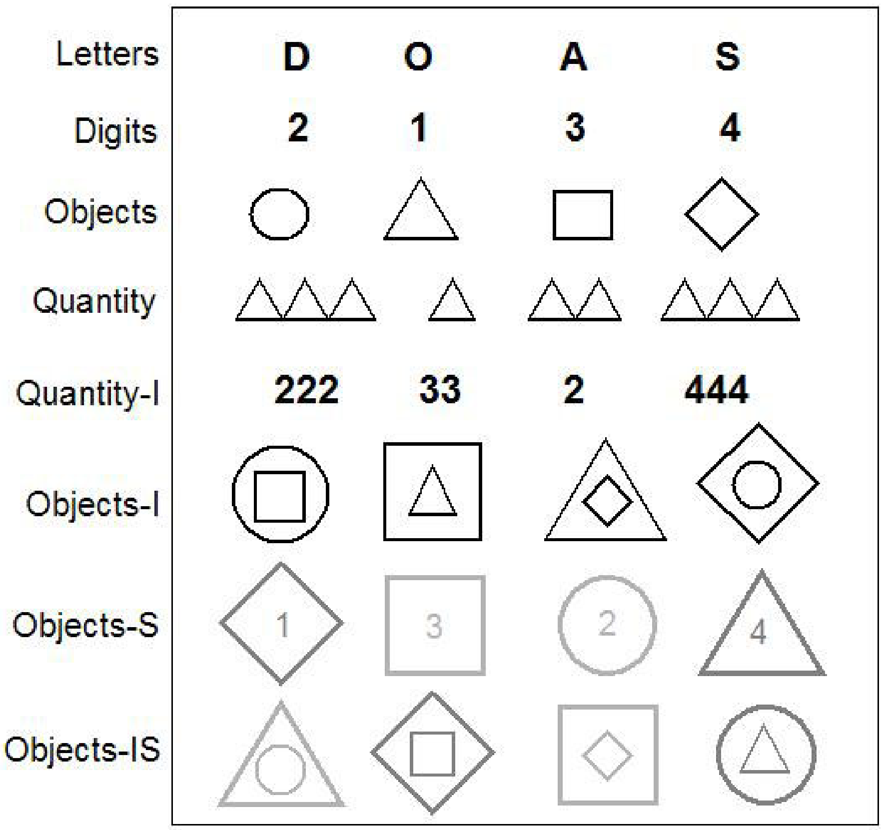

Figure 1. Examples of all control tasks and executive tasks that required the naming of symbols. For Objects-S and Objects-IS, light grey objects should be considered yellow, darker grey objects should be considered blue.

Inhibition

Two measures of inhibition were administered. The first inhibition task was previously used by Bull and Scerif (2001) and was a variation on the Quantity-task, the Quantity Inhibition task (Quantity-I). The second inhibition task was a variation on the Objects-task; the Objects Inhibition task (Objects-I).

Quantity-I. Instead of arrays of triangles, as in the Quantity naming task, arrays of digits were presented. The number of digits in the array did not correspond to the actual digits in the array. Again, subjects were instructed to name the *quantity* of the stimuli in the array. For example, if the array '222' was presented, the correct response was '3'. So, the number represented by the digits had to be inhibited in favor of the quantity of digits in the array. Extra time needed to complete the Quantity-I task, compared to the basic Quantity-task, was attributed to the requirement to inhibit one highly conditioned response (i.e., naming of digits), in favor of another response (i.e., naming of quantity) stemming from the same response set.

Objects-I. The same 4 geometrical objects as in the Object naming task, were alternately presented, but now an additional geometrical object was placed in the centre of the larger objects. Subjects were instructed to name the smaller object, i.e., they had to inhibit the larger, more prepotent objects in favor of the smaller, less noticeable ones. Extra time needed to complete the Objects-I task, compared to the basic Objects-task, was attributed to the requirement to inhibit the prepotent stimulus in favor of the less obtrusive stimulus from the same response set.

Shifting

Two measures of shifting were administered. One measure was a variation on the Object naming task; the Objects Shifting task (Objects-S). The other task was the Making Trails task.

Objects-S. The same 4 geometrical figures as in the Object naming task, were presented, but now a digit was placed in the centre of the figures. Either the figure or the digit had to be named, depending on the color of the stimulus. When the stimulus was yellow, the digit had to be named, when it was blue, the surrounding figure had to be named. Since objects and digits are not elements of the same response set, as is the case in the Objects-I condition, the extra time that was needed to complete the Objects-S task, compared to the basic Objects-task, was attributed to the requirement to shift between sets.

Making Trails. As second measure of shifting ability, a Making Trails task was used. We administered the paper and pencil version that was used previously by McLean and Hitch (1999). Subjects received two cards. One card (Trail A) contained 22 circles carrying a digit. Subjects were asked to start at the circle containing the number ‘1’ and make a trail with a pencil connecting the circles in ascending order (i.e., 1-2-3-4-5, etc.) as quickly as possible. The other card (Trail B) contained 22 circles carrying either a digit or a letter. Subjects were asked to start at number ‘1’ and make a trail with a pencil by alternately connecting circles with digits and letters in ascending order (i.e., 1-A-2-B-3-C etc.) as quickly as possible. Both trails were preceded by a sample trail consisting of 9 to-be-connected circles to explain the task. Performance on both tasks was timed, and time needed to complete the trails (rounded off to whole seconds) was used as test scores.

Inhibition and Shifting

We also administered an object naming task that required both inhibition and shifting. The Objects-I task was adjusted by introducing the shifting element from the Objects-S condition, resulting in the Objects Inhibition Shifting task (Objects-IS). Like in the Objects-I task, figures were presented with smaller figures in the center. This time, depending on the color, either the inner (yellow) or the outer (blue) figure had to be named. Extra time needed to complete the Objects-IS task, compared to the Objects task, the Objects-I task, and the Objects-S task, was attributed to the interaction between inhibitory and shifting task demands.

Procedure

The verbal analogies test and the ATT were administered group-wise. The OMRT was administered individually. All screening tests were administered on the same day.

Subsequently, the 8 naming tasks were presented in one test session. To prevent order effects, 4 orders were composed such that tasks demands were least likely to interfere. Those orders were divided equally over the 4 experimental groups. The Making Trails task was administered separately, approximately 2 weeks before the administrations of the naming tasks. For the same reason, order of Trail A an Trail B was varied but evenly distributed over the 4 experimental groups. All children were tested individually. Graduate students, who were trained prior to testing, administered the tests.

Results

The results are presented in two sections. In the first section, we attend to the results on the control tasks. In the second section, we present the results on the executive tasks.

Control tasks

Means and standard deviations of the four groups on the control tasks are presented in Table 2. In Figure 2, we have displayed for each group with learning disabilities the effect size d of its difference with the control group on each control task. Since the control group was used as reference group, we used the standard deviations of this group to compute the effect sizes, and no effect sizes appear for this group in the figure.

The scores on the four naming speed control tasks (Letters, Digits, Objects, and Quantity) and the Making Trails control task (Trail A) were subjected to a Multivariate Analysis of Variance (MANOVA) with Arithmetic ability (arithmetic disabled vs. non-arithmetic disabled) and Reading ability (reading disabled vs. non-reading disabled) as between subjects factors. This 2 x 2 multivariate analysis, instead of an analysis with four independent groups, was deemed necessary to test whether the performance of the group

Table 2
Mean reaction times (in seconds) and standard deviations for all tasks for chronological age controls (CA, n = 19), the group with arithmetic disabilities (AD, n = 18), the group with reading disabilities (RD, n = 21) and the group with reading and arithmetic disabilities (RAD, n = 16)

	CA		AD		RD		RAD	
Task	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Control								
Letters	19.72	2.98	20.24	3.45	22.47	3.77	23.39	4.63
Digits	18.36	3.04	19.65	2.69	19.59	3.89	24.33	5.43
Objects	39.38	7.72	43.64	9.57	43.84	9.00	45.82	7.63
Quantity	27.61	5.04	30.23	4.95	28.49	5.32	32.31	7.43
Trail A	24.16	9.21	25.72	8.43	24.14	8.42	25.50	5.83
Inhibition								
Quantity-I	37.15	15.04	44.89	9.13	38.81	4.57	46.13	9.02
Objects-I	41.45	8.61	44.79	9.59	45.36	8.87	49.83	11.62
Shifting								
Objects-S	46.04	5.39	51.15	9.57	52.58	9.71	57.88	9.51
Trail B	41.42	12.04	54.44	15.56	42.43	12.93	54.37	12.48
Inhib.+Shift.								
Objects-IS	67.58	11.20	81.98	22.01	76.50	16.19	88.49	22.15

with a double learning deficit (RAD) could be described as an additive combination of the deficits found in the groups with a single learning deficit (RD and AD), or was due to an interaction of impaired arithmetic and reading ability (see Willcutt et al., 2001, for a similar procedure). For significant effects, contrasts were specified in which the performance of each group with learning deficits (AD, RD, or RAD) was directly compared to the performance of the controls (CA).

The multivariate test for Arithmetic ability was significant (F(5, 66) = 3.25, p < .01, η_p^2 = .20). Univariate tests showed that children with arithmetic disabilities were slower than children without arithmetic deficits in the naming of Digits (F(1, 70) = 11.28, p < .01, η_p^2 = .14), and Quantity (F(1, 70) = 5.85, p < .05, η_p^2 = .08), but not in the naming of Letters (F(1, 70) < 1, *ns*), and Objects (F(1, 70) = 2.44, *ns*), or the making of Trail A (F(1, 70) < 1, *ns*). The multivariate effect for Reading ability was also significant (F(5, 66) = 3.16, p < .01, η_p^2 = .19). Univariate tests showed that children with reading impairments were slower than children without reading deficits in the naming of Letters (F(1, 70) = 11.59, p < .01, η_p^2 = .14), and Digits (F(1, 70) = 10.79, p < .01, η_p^2 = .13). A weak trend was found for Object naming (F(1, 70) = 2.76, p = .10, η_p^2 = .04). The performance of children with reading disabilities did not differ significantly from children without reading deficits on the Quantity-task (F(1, 70) = 1.24, *ns*), and Trail A (F(1, 70) < 1, *ns*).

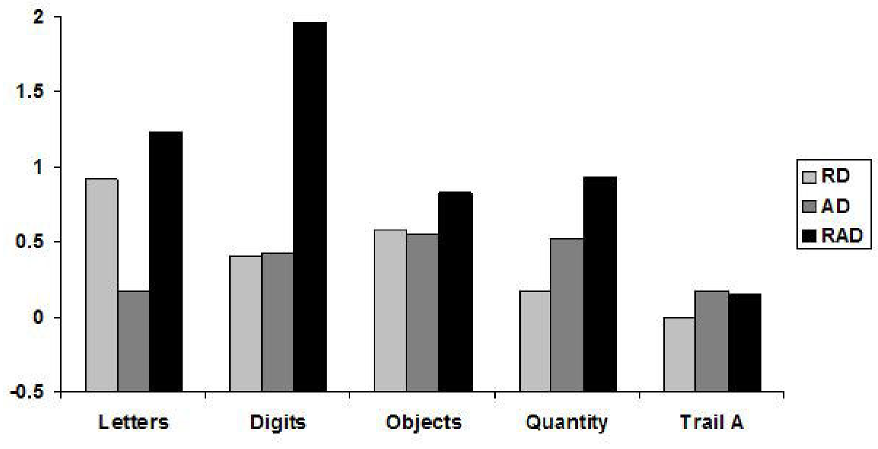

Figure 2. Effect sizes for the five control tasks, illustrating the difference in performance between the chronological age controls (n = 19) and children with reading disabilities (RD, n = 21), children with arithmetic disabilities (AD, n = 18), and children with disabilities in reading and arithmetic (RAD, n = 16). Note that the effect size for the chronological age controls is zero, and that the effect size scale starts at -0.5

The Arithmetic by Reading ability interaction was not significant (F(5, 66) = 1.31, *ns*), and neither were all accompanying univariate tests, apart from a trend for Digits (F(1,70) = 3.69, p = .06, η_p^2 = .05). This means that the poorer performance of the children with RAD on the naming tasks can be described as an additive combination of the performance of the children with AD and the children with RD.

Follow-up contrasts were specified in which the performance of the learning disabled groups was compared to the performance of the controls. Except for a significantly lower letter naming speed (t = 2.34, $p < .05$), the children with RD did not differ significantly from the control group on the control tasks. Similarly, the differences between the children with AD and the control group were not significant. The children with RAD, however, showed significantly slower naming speed than the control group on all control tasks that involved naming (Letters, t = 2.92, $p < .01$; Digits, t = 4.57, $p < .01$; Objects, t = 2.22, $p < .05$; Quantity, t = 2.43, $p < .05$). For Trails A, there was no significant difference between the groups (t = .48, *ns*).

Central Executive tasks

The means and standard deviations of the four groups on the CE tasks are presented in Table 2. The main issue of this section is whether the various groups are differentially affected by the additional CE requirements. Therefore, performance on the CE tasks is compared to performance on the control tasks. To illustrate the results, we computed the differences between the scores on the CE tasks and those on the control tasks for each group. These difference scores were deemed to reflect the pure effect of the extra CE requirement. For these difference scores, we computed per CE task for each learning disabled group the effect sizes of the differences with the control group. These effect sizes are displayed in Figure 3. Because the CA group functioned as reference group, the standard deviations of this group were used to compute the effect sizes, and no effect sizes appear for this group in the figure.

To assess the effects of the task manipulations of inhibition and shifting, MANOVAs for repeated measures were performed. In each of these analyses, a control task and a CE task constituted the within subjects factor (with or without CE requirement), whereas Arithmetic ability (arithmetic disabled vs. non-arithmetic disabled) and Reading ability (reading disabled vs. non-reading disabled) were entered as between subjects factors. Our main interest was in the interactions of the within subjects factor with the Arithmetic and Reading ability factors. These interactions would reveal differential reactions to the additional CE requirements of the CE tasks. Whenever interactions proved significant, the differential effect was studied in more detail through simple contrasts in which the mean difference between scores on the CE task and scores on the control task of the control group was compared to the mean differences of the separate learning disabled groups (RD, AD, and RAD).

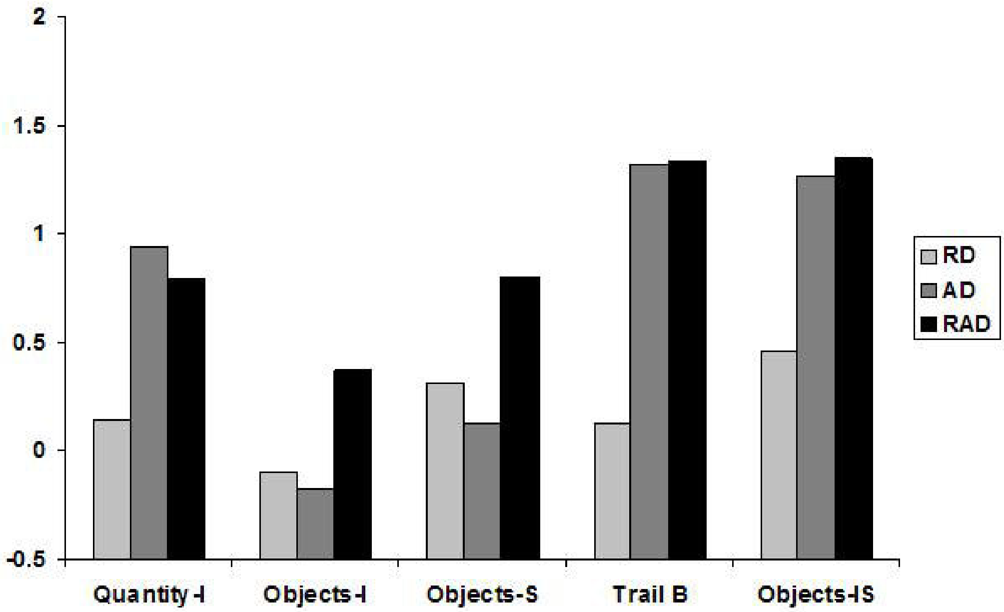

Figure 3. Effect sizes for the five executive tasks, illustrating the difference in reaction to the executive manipulation between the chronological age controls (n = 19) and the children with reading disabilities (RD, n = 21), the children with arithmetic disabilities (AD, n = 18), and children with reading and arithmetic disabilities (RAD, n = 16). Note that the effect size for the chronological age controls is zero, and that the effect size scale starts at –0.5.

We did not specify contrasts for the main effects of Arithmetic and Reading ability or for their interaction. These effects concern the average performance on the two tasks (the control and the CE task). In the absence of interactions of Reading ability or Arithmetic ability with the within subjects factor, the results would be similar to the results reported for the control tasks. In the presence of such an interaction, contrasts on the difference scores (as just described) are in this context more informative than contrasts on the mean scores.

Inhibition

Two inhibition tasks were administered: Objects-I, and Quantity-I. To assess the differential effects of the inhibition requirements on the performance of the four groups, performance on these inhibition tasks was compared to performance on the Object naming task and Quantity naming task, respectively. Thus, in the repeated measures MANOVAs reported below, Inhibition (task with or task without inhibition) constituted the within subjects factor.

Objects versus Objects-I. The main effect of Inhibition was significant (*F*(1, 70) = 7.87, p < .01, η_p^2 = .10). Naming speed on the Objects-I task was significantly slower than on the Objects control task. The main effect for Reading ability was also significant (*F*(1, 70) = 3.87, p < .05, η_p^2 = .05). Children with reading disabilities were slower in the naming of objects than children without reading problems. The main effect for Arithmetic ability approached significance (*F*(1, 70) = 3.15, p = .08, η_p^2 = .04), indicating a trend towards slower performance of children with arithmetic disabilities. The interaction between Arithmetic and Reading ability was not significant (*F*(1,70) < 1, *ns*).

The interactions of Inhibition with Arithmetic ability and Reading ability were not significant (both *F*(1, 70) < 1, *ns*), and neither was the Inhibition by Arithmetic by Reading ability interaction (*F*(1, 70) = 1.19, *ns*). So the inhibition-manipulation in the Objects-task did not have a differential effect on the performance of the groups.

Quantity versus Quantity-I. A main effect was found for Inhibition (*F*(1, 70) = 214.57, p < .001, η_p^2 = .75), indicating that quantity naming was significantly slower on the Quantity-I task than on the Quantity control task. The main effect of Arithmetic ability was also significant (*F*(1, 70) = 16.59, p < .001, η_p^2 = .19). Children with arithmetic disabilities were slower in quantity naming than children with normal arithmetic abilitiy. The main effect of Reading ability (F(1, 70) = 1,23, ns), and the Arithmetic by Reading ability interaction (*F*(1, 70) < 1, *ns*) were not significant.

The Inhibition by Reading ability interaction was not significant (*F*(1, 70) < 1, *ns*), and neither was the three-way Inhibition by Arithmetic by Reading ability interaction (*F*(1, 70) < 1, *ns*). In contrast, the Inhibition by Arithmetic ability interaction was significant (*F*(1, 70) = 6.86, p < .01, η_p^2 = .09). Children with arithmetic disabilities were significantly slower in quantity naming when inhibition was required (Quantity-I-task) as compared to their quantity naming performance without inhibition requirements (Quantity-task), than the children without arithmetic deficits.

Subsequently, contrasts were specified in which the performance of each disabled group was compared to that of the controls. These contrasts showed that the extra inhibition requirement of the Quantity-I task had the same decelerating effect on the naming speed of the controls and children with RD (t = .35, *ns*). However, the quantity naming speed of the children with AD had decreased significantly more as a result of the additional inhibition requirements than the naming speed of controls (t = 2.21, p < .05). A similar trend was found for the children with RAD (t = 1.79, p = .08).

However, in the previous section it was shown that children with arithmetic impairments had performed more slowly on the Quantity control task. The significant Inhibition by Arithmetic interaction might therefore merely reflect a proportional increase in naming time in reaction to the additional inhibition requirement. To examine this possibility, the scores on the Quantity and Quantity-I task were subjected to a logarithmic transformation. Such a transformation enables one to study proportional change in an analysis of variance because it converts a multiplicative effect (effect manipulation x score on control task) to an additive effect (effect manipulation + score on control task)[5], which in turn can be described through analysis of variance (Levine, 1993; Zar, 1999). Next, the MANOVA was redone on the transformed task scores. The pattern of results of this analysis was similar, except for the Inhibition by Arithmetic ability interaction, which was no longer significant ($F(1, 70) = 2.64$, $p = .11$). Thus, the relatively larger decrease in quantity naming speed in the children with arithmetic disabilities on the Quantity-I task appeared to be a function of their slower quantity-naming on the control task, and did not reflect a larger effect of the additional inhibition requirement.

Shifting

Two shifting tasks, Objects-S and Trail B, were administered. To assess whether the groups differed in their reaction to the extra shifting requirement, performance on these shifting tasks was compared to the performance on the control tasks Objects and Trail A, respectively. Thus, in the repeated measures MANOVAs reported below, Shifting (task with and task without shifting) constituted the within subjects factor.

Objects versus Objects-S. A significant main effect was found for the Shifting ($F(1, 70) = 101.18$, $p < .001$, $\eta_p^2 = .59$). Naming speed was slower on the Objects-S task than on the Objects control task. Also, both main effects for Arithmetic ability and Reading ability were significant ($F(1, 70) = 5.23$, $p < .05$, $\eta_p^2 = .07$, and $F(1, 70) = 7.47$, $p < .01$, $\eta_p^2 = .10$, respectively). However, the Arithmetic by Reading ability interaction was not significant ($F(1, 70) < 1$, *ns*). Thus, the performance of children with RAD could be considered an addition of the slower performance found in children with a single learning impairment.

The Shifting by Arithmetic ability interaction was not significant ($F(1, 70) = 1.44$, *ns*); children with arithmetic disabilities did not experience more difficulty with the additional shifting requirements than children without arithmetic deficits. The Shifting by Reading ability interaction approached significance ($F(1, 70) = 3.64$, $p = .06$, $\eta_p^2 = .05$). The three-way interaction of Shifting by Arithmetic by Reading ability interaction was not significant ($F(1, 70) < 1$, *ns*).

The Inhibition by Reading ability interaction was further investigated through contrasts. These contrasts showed that the effect of the extra shifting requirement in children with RD and children with AD did not differ

[5] Because of the rule ln(ab) = ln(a) + ln(b) multiplicative effects can be exhibited as additive

significantly from its effect in the control group (t = .89, *ns*, and t = .35, *ns*, respectively). However, in children with RAD the additional shifting requirement resulted in a significantly larger decrease in naming speed, compared to controls (t = 2.14, p < .05).

The possibility remained that the interaction of Shifting and Reading ability mainly reflected a proportional decrease in the naming speed of children with reading disabilities, since these children had also performed somewhat slower on the Object naming control task. Therefore, the MANOVA was redone on the log-transformed scores. In this analysis, the Shifting by Reading ability interaction was no longer significant (F(1, 70) = 1.34, *ns*). Accordingly, the larger decrease in the naming speed of the children with reading disabilities on the object-naming task with a shifting requirement (Objects-S) appeared to be a function of their initial slower object-naming speed on the control task (Objects).

Trail A versus Trail B. The main effect for Shifting was significant (F(1, 70) = 286.41, p < .001, η_p^2 = .80). The participants needed significantly more time to complete Trail B than to complete Trail A. The main effect for Arithmetic ability was significant (F(1, 70) = 10.22, p < .01, η_p^2 = .13), but the main effect for Reading ability and the Arithmetic by Reading ability interaction were not (F(1, 70) < 1, *ns*). So, overall, children with arithmetic disabilities were slower in the making of trails than children without arithmetic deficits.

The Shifting by Arithmetic ability interaction was significant (F(1, 70) = 16.05, p < .001, η_p^2 = .19), indicating that the requirement to shift in Trail B decreased the naming speed of children with arithmetic disabilities more than the naming speed of children without arithmetic deficits. Since the performance of the children with arithmetic disabilities on the control task, Trail A, did not differ from the performance of the children without arithmetic deficits (see above), the differential effect of the shifting requirement in Trail B could not be attributed to a proportional decrease in speed. None of the other interactions were significant (Shifting by Reading ability, F(1, 70) < 1, *ns*; Shifting by Arithmetic by Reading, F(1, 70) < 1, *ns*).

The Inhibition by Arithmetic ability interaction was further investigated through contrasts. These showed that the decrease in naming speed due to the additional shifting requirements did not differ between the controls and the children with RD (t = .27, *ns*). However, compared to controls, the decrease in naming speed was significantly larger in children with AD (t = 2.96, p < .01), and in children with RAD (t = 2.91, p < .01).

Inhibition and Shifting

The Objects-IS task required both inhibition and shifting. First, the effect of these CE requirements on the performance of the various groups was examined by comparing performance on the Objects-IS task to performance on the Objects control task, which did not require inhibition or shifting. For exploratory reasons, we also pursued whether a combination of CE requirements (Objects-IS) had a different effect on the naming speed of the groups than single CE requirements (Objects-I and Objects-S).

In the first MANOVA, Objects and Objects-IS constituted the within subjects factor Inhibition/Shifting (IS). A significant effect for IS was found (F(1, 70) = 511.09, p < .001, η_p^2 = .88). Mean naming speed was lower in the Objects-IS task than in the Objects naming control task. In addition, the main effect for Arithmetic ability was significant (F(1, 70) = 7.79, p < .01, η_p^2 = .10), meaning that children with arithmetic disabilities were significantly slower in object naming (Objects and Objects-IS) than children without these disabilities. A trend was found towards lower object naming speed for reading disabled children (F(1, 70) = 3.56, p = .06, η_p^2 = .05). The interaction of Arithmetic and Reading ability was not significant (F(1, 70) < 1, *ns*).

The IS by Reading ability interaction was not significant (F(1, 70) = 1.96, *ns*), and neither was the IS by Arithmetic by Reading ability interaction (F(1, 70) < 1, *ns*). However, the IS by Arithmetic ability interaction was significant (F(1, 70) = 10.30, p < .01, η_p^2 = .13). The naming speed of children with arithmetic disabilities had decreased significantly more than the naming speed of children without arithmetic disabilities as the result of the addition of two CE requirements to the task.

Follow up contrasts of the IS by Arithmetic disability interaction showed that the additional CE requirements of the Objects-IS task resulted in a significantly larger decrease in naming speed in children with AD and children with RAD relative to the decrease in naming speed of the chronological age controls (t = 2.26, p < .05, and t = 3.22, p < .01, respectively). For the children with RD, a trend towards a larger decrease in naming speed, compared to controls, was found (t = 1.69, p = .09).

This IS by Arithmetic ability interaction could not be due entirely to a proportional decrease because we did not find a significant difference between children with and without arithmetic disabilities on the Objects control task. Indeed, the interaction remained significant when the analysis was redone on the log-transformed scores (F(1, 70) = 5.12, p < .05, η_p^2= .07). However, contrasts showed that the percentage of change in naming speed due to the IS requirements was not different for children with RD and children with AD, compared to the control group (t = .24, *ns*, and t = 1.49, *ns*, respectively). Only the proportional change in naming speed of the children with RAD differed slightly from the CA group (t = 1.91, p = .06).

In a second analysis, we examined the differential effect of the additional shifting requirement of the Objects-IS task. Therefore, the scores on the task that required only inhibition, Objects-I, were compared to the scores on the task that in addition required shifting, Objects-IS. Naming speed appeared to be significantly slower on the Objects-IS tasks than on the Objects-I task (F(1, 70) = 384.84, p < .001, η_p^2 = .85). In addition, significant main effects were found for Reading ability and Arithmetic ability (F(1, 70) = 4.29, p < .05, η_p^2 = .06 and F(1, 70) = 8.44, p < .001, η_p^2 = .11, respectively). The interaction between Reading and Arithmetic ability was not significant (F(1, 70) < 1, *ns*).

The main effect of Arithmetic ability was qualified by a significant Arithmetic ability by Shifting interaction ($F(1, 70) = 7.49$, $p < .01$, $\eta_p^2 = .10$). The difference in naming speed between the children with and without arithmetic disabilities was larger on the Objects-IS task than on the Objects-I task, which did not require shifting. The other interaction effects were not significant (for both $F(1, 70) < 1$, *ns*). Follow up contrasts of the Arithmetic by Shifting interaction revealed that the effect of the extra shifting requirement was significantly larger in children with AD and in children with RAD than in controls ($t = 2.31$, $p < .05$, and $t = 2.54$, $p < .01$, respectively). For children with RD, the effect did not differ significantly from the effect on controls ($t = 1.09$, *ns*).

Because earlier analyses had indicated that the mean naming speed on Objects-I in the children with arithmetic disabilities was somewhat lower, the interaction of Arithmetic ability by Shifting was also examined for the log-transformed scores. In this analysis, the Arithmetic ability by Shifting interaction approached significance ($F(1, 70) = 2.97$, $p = .09$, $\eta_p^2 = .04$). So, the increase in the difference in naming speed between children with and without arithmetic disabilities from the Objects-I to the Objects-IS, as found for the non-transformed score, is not entirely a function of the difference found on the Objects-I task. Children with arithmetic disabilities were also more affected by the additional shifting requirement of the Objects-IS task than the children without arithmetic disabilities. However, follow up contrasts comparing the separate learning disabled groups with the control group, did not reveal any significant differences.

In a final analysis, the effect of an additional inhibition requirement was examined by comparing scores on the task that required only shifting, Objects-S, to scores on the task that in addition required inhibition, Objects-IS. This analysis revealed that object naming on the Objects-S task was significantly faster than on the Objects-IS task ($F(1, 70) = 221.85$, $p < .001$, $\eta_p^2 = .76$). In addition, main effects of Reading and Arithmetic ability were found ($F(1, 70) = 6.55$, $p < .05$, $\eta_p^2 = .09$ and $F(1, 70) = 10.77$, $p < .01$, $\eta_p^2 = .13$, respectively). Children with reading disabilities and children with arithmetic disabilities had a slower object naming speed than children without deficits in reading or arithmetic. The Reading ability by Arithmetic ability interaction was not significant ($F(1, 70) < 1$, *ns*).

The Inhibition by Arithmetic ability interaction proved significant ($F(1, 70) = 4.95$, $p < .001$, $\eta_p^2 = .07$), which means that the difference between children with and without arithmetic disabilities was larger on the Objects-IS than on the Objects-S task. The other interactions were not significant (for both $F(1, 70 < 1$, *ns*). Follow up contrasts of the significant Inhibition by Arithmetic interaction revealed that the extra inhibition requirement had slowed down the naming speed of children with AD and children with RAD slightly more than the naming speed of the controls ($t = 1.84$, $p = .07$, and $t = 1.74$, $p = .09$, respectively). The effect of the additional inhibition requirement on the naming speed of children with RD group did not differ from the effect on controls ($t = .49$, *ns*).

Because earlier analyses had indicated that the mean naming speed on Objects-S in the children with arithmetic disabilities was somewhat lower, the Shifting by Arithmetic ability interaction could reflect a proportional increase in the difference between the groups. Therefore, the analysis was also performed on the log-transformed scores. In this analysis the Inhibition by Arithmetic ability interaction was no longer significant ($F(1, 70) = 1.94$, $p > .15$, $\eta_p^2 = .03$). Accordingly, the increase of the difference in naming speed between the children with and without arithmetic disabilities from the Objects-S to the Objects-IS task mainly reflected a proportional increase and not a differential response of the groups to the additional inhibition requirement of the Objects-IS task.

In sum, the analysis of the Objects-IS task showed that children with arithmetic disabilities are significantly more affected by the extra CE requirements than children without arithmetic disabilities when the performance on the Objects-IS task is compared to the performance on the Objects control task, which does not require inhibition and shifting. For the separate groups we found that the effect in children with AD as well as in children with RAD was larger than in the control group. No differences were found between children with RD and the controls. When the scores on the Objects-IS task were compared to the scores on the Objects-I task, we found that the performance of the children with arithmetic disabilities was significantly stronger affected by the additional shifting requirement. This effect was not entirely due to a proportional decrease in task performance from Objects-I to Objects-IS. In contrast, the comparison of Objects-S and Objects-IS revealed that the differential effect of an additional inhibition requirement was mainly a function of the lower performance of the children with arithmetic disabilities on the Objects-S task.

Discussion

The purpose of the present study was to investigate the executive functions inhibition and shifting in children with and without learning disabilities. The performance of children with arithmetic disabilities (AD), children with reading disabilities (RD), and children with deficits in both reading and arithmetic (RAD), was compared to the performance of age-matched controls (CA). All executive measures consisted of a baseline condition and a manipulated condition that appealed to the executive functions under study. All tasks, except one, were rapid naming tasks.

Concerning the control tasks, the results of the present study demonstrate that arithmetic disabilities were most highly associated with slower naming of digits and quantity, while reading disabilities were associated with slower naming of letters and digits. Besides, none of the interactions between Arithmetic ability and Reading ability were statistically significant. This means that for these naming tasks, the score profile of children with a double learning deficit should be considered an additive combination of the score profiles of children with a single learning deficit. However, when the four experimental groups were considered separately, it was shown that, apart noticeably slower letter naming in children with RD, the naming speed of children with RD and children with AD did not differ significantly from the naming speed of controls on any of the naming tasks. Although the naming speed of children with RD and AD was for all tasks somewhat lower than the speed of controls, these differences were, when studied separately, too small to result in statistically significant effects. Children with RAD, in contrast, were slower than the control group in the simple naming of all stimuli, irrespective of their nature: letters, digits, objects, or quantities. Based on the absence of effects for the children with a single learning deficit alone, one would be inclined to interpret this generally poorer performance of children with a double deficit as indicative for the presence of deficits that children with a single learning deficit do not experience. Yet, the absence of significant Arithmetic by Reading interactions indicates that this interpretation would be incorrect. The naming problems of children with RAD should be interpreted as an additive combination of the slightly poorer naming speed of children with RD and children with AD.

Problems with rapid naming are well documented for children with reading disabilities (see Wolf & Bowers, 1999, for a review), and previous studies have also reported naming speed deficits in children with AD on tasks appealing to their specific deficit: the naming of quantity (Hitch and McAuley, 1991), and the naming of digits (Bull and Johnston, 1997). Simple naming speed is often subsumed under phonological processes, and thus considered as an indication of the speed with which phonological codes are retrieved from long-term memory (e.g., Aarnoutse, van Leeuwe, & Verhoeven, 2000; de Jong & van der Leij, 1999; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; van de Bos, Zijlstra, & Lutje Spelberg, 2002). Deficits in naming speed are interpreted as deficits in the rapid recognition and retrieval of visually presented (linguistic) stimuli (Wolf & Bowers, 1999). Some authors (e.g., Wolf & Bowers, 1999; Neuhaus & Swank, 2002) have suggested that naming tasks are essentially basic reading tasks (e.g., letter reading instead of word reading), and as such almost as complex as any regular reading task. The strong and consistent relation between naming speed and reading capacity is thus explained by the analogy between the naming process and the reading process. Yet, this analogy does not explain why arithmetic ability is associated with slower naming of numerical stimuli. We consider the following possibilities. First, it is conceivable that children with arithmetic disabilities are less familiar with numerical symbols or concepts, because of their deficit. However, since the present digit-naming task involved only the first four, well known digits (1, 2, 3, and 4), and the quantity-naming task involved only small quantities (1 to 4), it seems unlikely that naming speed in children with arithmetic disabilities was affected by differences in familiarity. Second, a history of poor performance in enumeration tasks might have prompted children with arithmetic impairments to adopt a slower, less error-prone, mode of responding to numerical stimuli in general. Concerning the naming of digits, McCloskey (1992) argued that the mapping and naming of Arabic and verbal numerals is quite complex since the same digit can have different functions (e.g., the '1' denotes tens in '210' and '210.000' but not in '2100') and is pronounced differently (e.g., '2', '12') depending on the position of the digit. In this respect the naming of digits differs from the naming of objects. Although the pronunciation of letters also depends on their position within a word, different positions do not make the letters conceptually different, as is the case with digits. Besides, when viewed in isolation single letters do not have meaning, but single digits do. The tardiness of children with arithmetic problems with respect to the naming of digits, but not letters and objects, might thus result from the relatively difficult, and conceptually different, identification process of stimuli of which the meaning and pronunciation depends on the context. On the other hand, their slowness might also simply result from caution, induced by their history of failure, toward correct identification of numerical stimuli.

Regarding the naming of quantities, it is noteworthy that the arrays of stimuli in this study were all within the so-called ‘subitizing range’. Subitizing, which involves the immediate apprehension of the number of stimuli, is a fast and accurate strategy for the enumeration of small numbers of objects (1 to 4). Counting, on the other hand, is accurate, but slow, and is adopted with larger numbers of stimuli (e.g., Piazza, Mechelli, Butterworth, & Price, 2002; Starkey & Cooper, 1995; Svenson & Sjöberg, 1983). In view of this, it is possible that children with arithmetic deficits used the slower counting strategy instead of the faster subitizing strategy in at least part of the quantity-naming task. Whether the children with arithmetic disabilities in our study were slower in subitizing, or whether they (occasionally) reverted to a safer counting strategy, cannot be determined with the present data. Both options merit further consideration as they may explain the slower naming of quantity within this specifically disabled group.

In sum, the current results suggest relations between reading ability and the naming of letters and digits, and arithmetic ability and the naming of digits and quantities, respectively. Children with learning deficits in both reading and arithmetic exhibit the combination of these problems, as a result of which they experience general naming problems. Studies in which the different components of the naming process are separated (e.g., pause time, articulation time, and consistency of pause time, see Neuhaus, Foorman, Francis, & Carlson, 2001, and Neuhaus & Swank, 2002) might clarify the variability in the naming speed of different kinds of stimuli, and elucidate the nature of the naming problems in learning disabled children.

So far, we have focussed on the results of the control tasks. Before we turn to the results of the separate executive tasks, it is noteworthy that, as for the control tasks, none of the Arithmetic ability by Reading ability interactions were statistically significant for the executive measures. This means that the score profile of children with RAD should for all executive measures be considered a simple additive combination of the profiles of children with AD and children with RD. In other words, every time that the results showed that children with RAD reacted differently to the executive manipulations than the controls, this different reaction should be considered a simple additive combination of the reactions that children with AD and children with RD had displayed.

The inhibition task involving the naming of quantity was adapted from Bull and Scerif (2001). These authors reported a significant correlation of -.46 between arithmetic ability and the speed of quantity-naming in the interference condition. They also reported that the relation between arithmetic ability and performance on the interfering condition of the Stroop-task was not significant. Our findings are in line with these results. None of the groups with arithmetic disabilities (AD and RAD) experienced difficulties on the Objects-I task, which might, like the Stroop, be considered a deficit-neutral condition. Yet, the ability to name quantity in interfering task conditions proved to be impaired in both groups with arithmetic disabilities. In addition, our results also indicated that their slower quantity naming in the face of interference was a function of their somewhat poorer performance on the control task, Quantity, rather than a problem with inhibition per se. This means that the increase in response time in children with arithmetic deficits was indeed larger than that of children without arithmetic deficits, but, when related to their lower scores on the control task, not proportionally different.

The ability to inhibit prepotent or overlearned responses does not seem impaired in children with a single reading deficit. Their performance was affected by the additional inhibition requirements to the same degree as the performance of peers without learning deficits, irrespective of the nature of the stimuli.

Children with RAD, but not children with AD, performed more slowly than controls on the Objects-S shifting task. Yet, this slower naming of objects in the shifting condition proved to be a function of these RAD children's somewhat poorer performance on the Objects control task, rather than a problem with shifting per se. Despite the (proportionally) comparable performance of children with AD and RAD on the object naming tasks that required only one executive function (Objects-I and Objects-S), both groups of children with arithmetic deficits performed more poorly than controls on the task that appealed to both inhibition and shifting (Objects-IS). The requirement to handle inhibition and shifting demands simultaneously seems analogous to what Kane and Engle (2003) called 'active maintenance of task goals in the face of competition'. That is, in the Objects-IS task, participants needed to keep the task goal to shift between naming the inner and outer objects (depending on their color) active, while at the same time resolving the competition between naming the one object, while ignoring the other. Kane and Engle studied the influence of the percentage of congruent versus incongruent trials in a Stroop task on the performance of individuals with either high or low working memory span. The authors found that tasks including large numbers of congruent trails seemed to result in a tendency to neglect of the requirement to 'ignore the word', resulting in more errors on the sporadic incongruent trials, especially in low span individuals. Tasks including large numbers of *incongruent* trials seemed to reinforce the task goal, and to minimize the effort to maintain an active task goal. In this context, differences between high and low span individuals became apparent only in latency and not in accuracy.

In our study, all trials of the singular executive task Objects-I were incongruent. That is, the inner and outer objects were never alike. It can therefore be argued that in these tasks a context was created that reinforced the task goal; one can focus on the inner, and ignore the outer object. In the Objects-IS task, however, the goal to shift between naming the inner or outer object (depending on the color of the stimulus) had to be maintained in the face of competition resolution, i.e., the competition between naming one object and ignoring the other. It seems that children with arithmetic disabilities, like low-span individuals, experience difficulty with goal maintenance in the face of interference. The results of the analyses in which the scores on Objects-IS were compared to performance on Objects-I and Objects-S separately, strengthen this hypothesis. These analyses suggested that the poorer performance of children with arithmetic disabilities on the Objects-IS task was mainly due to the addition of a shifting requirement to an inhibition task, rather than the addition of an inhibition requirement to a shifting task. That is, adding the requirement to maintain the goal to shift (dependent on the color) between the inner and outer object to a competition-resolution task, influenced the naming speed of children with arithmetic disabilities more than the addition of a competition-resolution requirement to a task that already required task goal maintenance. However, the differential effect of the various manipulations might also be the result of the effectiveness of the different manipulations themselves. In addition, it must be noted that the effects were rather small. Further research into the problems that children with arithmetic deficits experience with shifting in the face of inhibition is therefore essential.

Despite the normal performance of children with AD and children with RAD on the Objects-S shifting task, both groups, as in earlier studies (e.g., McLean & Hitch, 1999), performed more poorly than controls on the other shifting task, the Making Trails task. Since the testing material of both Making Trails and Objects-S contained digits, and scores on the Digits task were not related to Making Trails scores, poor performance on the Making Trails task cannot be attributed to a domain-specific deficit. However, the Making Trails task is a complex task (Baddeley, 1996). It requires shifting between schemata (i.e., complex structures of knowledge about the alphabet, the numerical system, and its order), while the Objects-S tasks only requires shifting between sets (i.e., collections of unordered stimuli). In addition, successive responses in the Objects-S task are mutually independent while successive responses in the Making Trails task are dependent. That is, in the Making Trails task one needs to keep track of what responses have been given to be able to select the next response. For example, when 1, 2, and 3 have been passed, the next numerical response should be 4. This requirement to keep track of former responses and select responses accordingly, appeals to another executive function, namely updating. Furthermore, one might argue that the

Making Trails task induces negative priming. Negative priming refers to poorer performance that results when a response demands the handling of recently inhibited information; information that had to be inhibited on trial n-1 is relevant in trail n. In the Making Trails task, the shifting requirement, combined with the requirement to pay attention to the order of the stimuli, requires one first to inhibit a response, and then to reactivate it. For instance, 1 is not followed by 2, as usual, but by A; 2 has to be inhibited. Subsequently, A is again to be followed by the earlier inhibited response 2. The Object-S task does not require updating, and negative priming is not present in this task. So while the Objects-S task seems to require nothing but shifting, the Making Trails task appears to appeal to updating ability and (reversed) inhibition as well, and might thus be a less pure measure of shifting.

The Making Trails task and the Objects-IS task seem to share the requirement to monitor and regulate different executive functions simultaneously. The frequently reported association between arithmetic disability and executive dysfunctioning as measured by complex tasks like the Making Trails task and the Wisconsin Card Sorting Task (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; McLean & Hitch, 1999) might therefore be the result of the requirement to shift and inhibit (and update) at the same time. That is, to shift in the face of selection, or, to use Kane and Engle's phrasing, to maintain task goals active in the face of competition. Whether the inability to maintain goal information is limited to a context of inhibition, or whether the inability to activate and coordinate several executive functions simultaneously should be considered a failure of the fourth executive function distinguished by Baddeley (1996), namely, dual task performance, merits further research.

In children with a specific reading disability, the ability to shift between responses or response sets, whether in the context of inhibition or not, was not defected. That is, children with RD performed as well as controls on the Objects-S task, the Making Trails task, and the Objects-IS task.

In studies such as the present, the question to what extent the results can be attributed to the methods used to select the experimental groups in the first place, is legitimate. That is, are the reported effects the result of the learning disabilities under study, or of the methods used to select the groups? While the reading test that was used to screen and select participants is unlikely to have required the executive functions under study, this is less certain in the case of the arithmetic screening test. Even though we made sure to select an arithmetic test that did not contain complex multi-step problems, or require shifting between strategies or procedures, even elementary arithmetic sometimes requires borrowing or carrying, which might invoke the use of executive functions. That is, the process of arithmetic may *in itself* appeal to executive functioning more than the process of reading does. Selection of arithmetic disabled subjects might therefore imply, to a certain extent, selection of children who experience difficulty with executive functioning. However, some appeal to executive functions in arithmetic tests seems inevitable and we do belief that the arithmetic screening test as used in the present study, did so in the most limited way, without becoming trivial. Therefore, the possibility that the executive problems of the children with arithmetic disabilities in the current study are the result of the selection procedure seems very slight.

In sum, the current study shows that children with a specific reading disability are not characterized by deficits in inhibition or shifting. Children with arithmetic disabilities did not experience problems with inhibition or shifting per se. However, complex executive tasks that required the combination of executive functions did result in performance that was below that of controls. The question of whether this poorer performance was due to temporary loss of task goal information in a context of competition resolution, or to a more general inability to activate and coordinate different executive functions at the same time may be addressed in future research. Furthermore, the lack of significant interactions between Arithmetic ability and Reading ability suggests that the performance profile of children with a double learning deficit is best described as an additive combination of the deficits that children with a single learning impairment experience. These results suggest that the deficits of children with a double learning disability are not of a different nature from those of children with a single learning deficits yet sometimes are more prominent. It must be noted that this inference can be made only when the performance of children with single and double learning deficits is compared simultaneously within one study. When studies incorporate only a subset of children with learning deficits, the larger problems that children with RAD experience may be inaccurately interpreted as qualitatively distinct from the smaller (and sometimes insignificant) problems that characterize children with AD and children with RD. Finally, this study illustrates how performance on executive tasks may be a function of the ability to handle additional non-executive task requirements. The issue of task impurity should be considered carefully in the study of executive functioning, particularly in the context of learning disabilities. The use of control tasks when measuring executive ability is suggested.

4

Executive functioning in children, and its relations with reasoning, reading, and arithmetic [6]

This study investigated whether the executive functions (EFs) inhibition, shifting, and updating are distinguishable in children aged 9 to 12. Furthermore, the relations between these EFs and reading, arithmetic, and reasoning were examined. Measures for inhibition and shifting involved rapid naming tasks with or without executive requirements. Updating measures were adapted from Miyake et al. (2000). Confirmatory factor analysis was used to part variance resulting from executive and non-executive task requirements. Factors for Shifting and Updating, but not Inhibition, were detectable in the presence of a non-executive Naming factor. Updating was related to reading, arithmetic, and verbal and non-verbal reasoning. Shifting was exclusively related to non-verbal reasoning. Reading and arithmetic were, however, primarily related to the non-executive task elements of the executive measures.

[6] van der Sluis, S., de Jong, P.F., & van der Leij, A.
Submitted

Introduction

Executive functions (EFs) are defined as the regulatory processes responsible for organizing and monitoring the processing of information, and controlling and coordinating cognitive processes during the performance of complex cognitive tasks (e.g., Lindsay, Tomazic, Levine, & Accardo, 1999; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). In adults, EFs have been studied with regard to their structure (e.g., Miyake et al., 2000; Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000; Oberauer, Süß, Wilhelm, & Wittmann, 2003; Süß, Oberauer, Wilhelm, Wittmann, & Schulze, 2002), and their relations with reasoning ability, i.e., IQ or 'g' (e.g., Colom, Rebollo, Pallacios, Juan-Espinoza, & Kyllonen, 2004; Conway, Cowan, Bunting, Therriault, Monkoff, 2002; Engle, Laughlin, Tuholski, & Conway, 1999; Kyllonen & Christal, 1990). Most of these studies have been conducted in non-clinical samples. In contrast, most EF studies in children concern clinical samples, e.g., children with learning deficits in reading and arithmetic (e.g., Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Sikora, Haley, Edwards, & Butler, 2002; van der Sluis, de Jong, & van der Leij, 2004; van der Sluis, van der Leij, & de Jong, in press), or children with attention deficit / hyperactivity disorder (e.g., Scheres et al., 2004; Shallice et al., 2002; Sonuga-Barke, Dalen, Daley, & Remington, 2002; Stevens, Quittner, Zuckerman, & Moore, 2002; Wu, Anderson, & Castiello, 2002). The few studies that did address executive functioning in non-clinical samples of children have focused on the development of executive performance with age (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Bedard et al., 2002; Christ, White, Mandernach, & Keys, 2001; Jacques, & Zelazo, 2001; Klenberg, Korkman, & Lahti-Nuuttila, 2001; Levin et al., 1991; Welsh, Pennington, & Groisser, 1991). In some of these studies, reasoning ability was involved as a covariate, but the relationship between reasoning and executive functioning in children has not been explicitly addressed. Similarly, little is known about the relationships of EFs with reading and arithmetic ability in normally functioning children. These scholastic abilities may not be of primary interest in adults, but as these abilities are still developing in children, they are considered core abilities in young populations and as such, they merit attention.

In the current study, the structure of executive functioning is examined in a non-clinical sample of children. In addition, the relationships are explored between individual differences in EFs, and individual differences in verbal and non-verbal reasoning ability, arithmetic ability, and reading ability.

Below, we first discuss the recent literature on the structure of executive functioning, the relations of the individual EFs with reasoning ability, reading, and arithmetic ability, and the problems that are encountered in measuring EFs.

The structure of executive functioning

Executive functioning is often used as a general term for a wide variety of meta-cognitive processes such as planning, organized search, impulse control, goal directed behavior, set maintenance, flexible strategy employment, selective attention, attentional control, initiation of actions, inhibition, fluidity, and self-evaluation (e.g., Letho, Juujärvi, Kooistra, & Pulkkinen, 2003; Sikora et al., 2002; Wu et al., 2002). Baddeley (1996) proposed to narrow down this proliferation of executive processes to four more general EFs: shifting, inhibition, updating, and dual task performance. Baddeley considered these four EFs to be subroutines of the 'central executive', a modality-free supervisory system, which acts as one of the defining components in the working memory model (Baddeley & Hitch, 1974), and which is involved in regulating and monitoring complex cognitive processes (e.g., Baddeley, 1996; Miyake et al., 2000). *Shifting* is defined as the ability to switch between sets, tasks, or strategies, i.e., the disengagement of an irrelevant task set, and the subsequent activation of a new, more appropriate one. Several subtypes of *inhibition* have been distinguished (e.g., Friedman & Miyake, 2004; Nigg, 2000). In the context of executive functioning and control, the focus has been on the ability to deliberately suppress dominant, automatic, or prepotent behavioral responses in favor of more goal-appropriate ones. Types of inhibition that cannot be considered deliberate, such as negative priming (longer reaction times in response to recently ignored or suppressed stimuli) and reactive inhibition (tendency to suppress previous responses) are usually not regarded as executive in nature (Miyake et al., 2000). *Updating* is defined as the ability to monitor and code incoming information for relevance to the task at hand, and the subsequent revision of the content of memory by replacing old items with newer, more relevant information. Updating thus concerns the dynamic, goal directed manipulation of the content of memory. The ability to coordinate performance on two tasks simultaneously is referred to as *dual task performance*. Dual task performance is indicated by the extent to which performance on a baseline task deteriorates when a secondary task is introduced that has to be performed simultaneously. The first three EFs are generally acknowledged as simple, lower level executive abilities, yet the status of dual-task performance as lower level EF is disputed (see for example, Miyake et al., 2000; Rabbitt, 1997).

Whether the EFs can indeed be taken as distinct functions, has been studied in adult subjects by Miyake et al. (2000). In a confirmative factor analysis (CFA) the authors established three latent factors: inhibition, shifting, and updating. Dual task performance did not emerge as a stable factor. The factors for inhibition, shifting, and updating were moderately correlated, which suggests that the factors are distinguishable, and yet share some underlying commonality.

Unlike this study by Miyake et al. (2000), most studies on the structure of EFs, especially in children, have used exploratory factor analysis (e.g., Anderson et al., 2001; Klenberg et al., 2001; Levin et al., 1991; Welsh et al., 1991). These studies are based on samples of different (often wide) age-ranges, and the factorial solutions reported differ in the number of factors extracted (ranging from 3 to 5 factors), and the meanings attached to the factors. For instance, Levin et al. (1991) performed exploratory factor analysis (EFA) on EF data obtained in 7- to 15-year old children. Three factors were extracted, which the authors referred to as 'semantic association and concept formation', 'freedom from perseveration', and 'planning and strategy'. The study by Klenberg et al. (2001), in a sample of 3- to 12-year old children, produced a four-factor solution with factors for 'fluency', 'selective visual attention', 'selective auditory attention', and 'simple motor inhibition'.

Only a few studies on executive functioning in children have used CFA. Manly et al. (2001) performed CFA as part of a study on the validation of the test of everyday attention for children (TEA-Ch). Based on the performance of children aged 6 to 16, three related yet separate factors were distinguished: selective attention, attentional control/switching, and sustained attention. Letho et al. (2003) performed CFA on EF data gathered in children aged 8 to 13. These researchers distinguished factors for inhibition, shifting, and working memory, the latter being comparable to updating ability. Again, the factors proved related but separable.

The factorial solutions of both CFA studies in children show some resemblance with the results as obtained in the adult sample by Miyake et al. (2000). Yet, Letho et al. (2003, p.75) noted that the use of different task sets, and the complex, multifarious nature of EF tasks (i.e., 'impure' measures) complicate the comparison of factorial solutions, either obtained through EFA or CFA. We will return to the issue of 'task impurity' below.

EFs and their relations with reasoning, reading, and arithmetic

Many studies, mainly in adult populations, have addressed the relation between general working memory (WM) capacity and reasoning ability (or general intelligence, or g) (e.g., Colom et al., 2004; Conway et al., 2002; Engle et al., 1999; Kyllonen & Christal, 1990; Oberauer and colleagues, 2000, 2003; Süß et al., 2002). In these studies, usually no distinction is made between the three EFs that are proposed as subroutines of the WM system. In the majority of studies on WM, complex span tasks (i.e., mnemonic tasks) like reading span and counting span, or tasks that require the revision of the content of memory are used to assess WM capacity. As such tasks are usually regarded as measures of updating ability, we cautiously consider these results on general WM capacity as informative about the relation of updating ability with reasoning.

Many authors have reported strong correlations (over .80) between general reasoning ability and updating ability in adults (e.g., Colom et al., 2004; Kyllonen, 1993; Kyllonen & Crystal, 1990; Süß et al., 2002;). In children, the correlation between updating ability and reasoning is also strong. For instance, de Jong & Das-Smaal (1995) report a correlation of .66 between updating and reasoning in 9 year olds. The strength of these relations has led some authors to question the distinction between the two constructs while others argue that the WM/updating construct may be used to reveal the very essence of g (e.g., Deary, 2002; Kyllonen, 2002). Yet, updating ability and reasoning ability have been found to relate differently to other cognitive abilities. For example, Kyllonen and Christal (1990) found that reasoning ability related more strongly to general knowledge than updating ability, whereas updating ability related more strongly to processing speed than reasoning ability. Likewise, Engle et al. (1999), and Conway et al. (2002) showed that updating ability was strongly related to both short-term memory (STM) capacity and reasoning ability, whereas the correlation between STM and reasoning was weak.

Updating ability has also been related to linguistic abilities such as comprehension and reading (e.g., Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Swanson, 1999), verbal ability (e.g., Cantor, Engle, & Hamilton, 1991), and vocabulary (e.g., Gathercole & Pickering, 2000). With respect to reading, updating is believed to support the encoding process, especially when reading is not yet fully automatized, and when unfamiliar words have to be read (e.g., de Jong, 1998; Siegel & Ryan, 1989). For the early reader, the word decoding process is still a chore, and segments of words have to be memorized while remaining segments are decoded. Although the involvement of updating in the act of reading does not necessarily imply that reading disabilities coincide with deficits in updating ability, several studies report poorer updating performance in children with reading disorders when compared to chronological age controls (e.g., de Jong, 1998; Howes, Bigler, Lawson, & Burlingame, 1999; Howes, Bigler, Burlingame, & Lawson, 2003; Siegel & Ryan, 1989; Swanson, 1999; Swanson & Ashbaker, 2000). Yet, others did not find any differences after controlling for age, IQ, and arithmetic ability (e.g., van der Sluis et al., in press; Wimmer & Mayringer, 2002).

With regard to arithmetic ability, updating has been argued to be involved in the solution of arithmetic problems in general, and multi-step problems in particular. Updating ability is supposed to support the memorization of numbers and subsolutions during the arithmetic process (e.g., Geary, 1993; McLean & Hitch, 1999). In studies with arithmetic disabled children, some report poorer performance in comparison with controls on complex span tasks (e.g., McLean & Hitch, 1999; Siegel & Ryan, 1989; Swanson, 1994). However, others report that differences in updating ability between children with, and without arithmetic deficits were absent when differences in age, IQ, and reading ability were controlled for (e.g., Bull et al., 1999; van der Sluis et al., in press).

Inhibitory capacity has been addressed in the context of learning disabilities in reading (e.g., Everatt, Warner, Miles, & Thompson, 1997; Helland & Asbjørnsen, 2000; van der Sluis et al., 2004; van der Schoot, Licht, Horsley, & Sergeant, 2000, 2002; Willcutt et al., 2001), and arithmetic (e.g., Bull & Scerif, 2001; Sikora et al., 2002; van der Sluis et al., 2004). With regard to reading, the general finding is that inhibitory ability, usually measured with the Stroop Color/Word test, is poorer in children with reading problems than in controls. However, these differences are found to disappear when variables like IQ, general naming speed, receptive language skills, or the presence of ADHD, are controlled for. With regard to arithmetic, children with arithmetic disabilities have been found to score less well on inhibition tasks than controls, especially when these tasks require numerical skills (Bull & Scerif, 2001). Yet, other authors report the disappearance of differences in inhibitory capacity after initial differences in numerical skills were controlled for (van der Sluis et al., 2004).

Shifting ability has also has been studied in the context of arithmetic disorders (e.g., Bull et al., 1999; Bull & Scerif, 2001; McLean & Hitch, 1999; van der Sluis et al., 2004). These studies show that arithmetic disabilities coincide with poorer performance on complex shifting tasks like the Wisconsin Card Sorting Task (WCST) and the Making Trails task. Shifting is therefore believed to support alternation between arithmetic strategies (e.g., addition, subtraction, multiplication), and arithmetic sub-solutions in multi-step arithmetic problems. Yet, van der Sluis et al. (2004) failed to find differences between children with, and without arithmetic disabilities on a very simple shifting task.

The few studies that have addressed the link between shifting ability and reading skill (e.g., van der Sluis et al., 2004; Weyandt, Rice, Linterman, Mitzlaff, & Emert, 1998; Klorman et al., 1999; Willcutt et al., 2001) have produced mixed findings. Results included poorer shifting performance in children with reading deficits in comparison to controls, no differences between those groups, and the disappearance of differences in shifting ability once differences in IQ, general naming speed, and additional disorders like ADHD are controlled for.

In sum, in children the relations of the three EFs with reading and arithmetic have mainly been addressed in the context of learning disabilities. In these studies, reasoning ability usually functions as an important covariate, while its relations with the individual EFs are not the primary topic of investigation. It therefore remains to be established how reasoning, reading, and arithmetic ability are related to inhibition, shifting, and updating in normally functioning children.

Problems in the assessment of EFs

Studying executive functioning has turned out to be far from easy. EFs have been said to lack construct validity, and EF tasks are characterized by low intercorrelations, and low test/retest reliability (e.g., Rabbitt, 1997). One of the fundamental measurement problems (e.g., Denckla, 1994; Miyake et al., 2000; Rabbitt, 1997) is the 'task impurity problem'. Because EFs need a task context to become manifest, they inevitably appeal to other, non-executive cognitive abilities such as verbal ability, motor speed, or visual-spatial ability. In addition, EF tasks often appeal to more than one EF at the time. Finally, the task designs used to evaluate EFs, especially those of measures of inhibition and shifting, differ widely between and within functions. Because EF tasks are complex and multi-cognitive in nature (i.e., are 'impure'), and differ greatly in their background demands (Burgess, 1997), performance on EF tasks cannot be readily attributed to the absence or presence of specific executive capacities.

Researchers in the field of EF have proposed two principal means of tackling the task impurity problem. Firstly, the use of CFA has been advocated as a way of dealing with the impurity of EF tasks (e.g., Rabbitt, 1997). CFA can be used to extract the common variance of EF indicators that are *presupposed* to appeal to the same underlying EF, even though they differ greatly in non-executive requirements. However, as we already indicated briefly, the use of CFA does not guarantee that the extracted common variance of a set of complex EF tasks is attributable to one executive ability only. For example, when the Tower of London (TOL) and the Matching Familiar Figures Test (MFFT) are used as indicators of an inhibition factor in CFA (Letho et al., 2003), one cannot claim that the resulting factor is merely indicative of inhibitory ability. The TOL has been described as a measure of planning, monitoring, self-regulation, and problem solving (Klenberg et al., 2001), and as a multi-cognitive task, which includes visual perception, attention and working memory besides strategic planning (Sikora et al., 2002). The MFFT has been described as a measure of visual search, hypothesis testing and impulse control (Welsh et al., 1991) besides as a test for inhibitory processes. The communality of these two tasks, as captured by CFA, could thus be attributed to a variety of different cognitive abilities besides inhibitory capacity.

So, although theory-driven CFA is undoubtedly a powerful tool, the problems that go with the use of complex EF tasks, i.e., task that appeal to several (non) executive abilities simultaneously, are not necessarily solved through the use of CFA.

As a second way of dealing with the task impurity problem various authors (e.g., Denckla, 1996; Pennington & Ozonoff, 1996; Scheres et al., 2004; Sergeant, Geurts, & Oosterlaan, 2002) have advocated the use of control tasks. In this task design, performance on a control task is compared to the performance on an executive task, which only differs from the control task in its additional appeal to an EF. In subsequent analyses, the focus is on the difference between the performance on the EF task and its control counterpart. The significance of accounting for performance on control tasks has frequently been illustrated. For example, while some authors report greater Stroop-like interference in learning disabled children (e.g., Bull & Scerif, 2001; Everatt et al., 1997), children with ADHD (see Sergeant et al., 2002 for a review), or older persons (e.g., Christ et al., 2001; West & Baylis, 1998), few found evidence for differential performance when initial differences in basic naming speed, as measured by the control task, were controlled for (e.g., Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Graf & Uttl, 1995; Seidman, Biederman, Monuteaux, Weber, & Faraone, 2000; Uttl & Graf, 1997;

van der Sluis et al., 2004; Willcutt et al., 2001). These findings show that differences (between groups) in performance on executive tasks can be a function of differences in the ability to handle additional non-executive task requirements.

The present study

Summarizing, studies on EFs have addressed the structure of EFs in children, but the use of complex EF tasks thwarts the interpretation of these results. In addition, in children the relationships of updating, inhibition, and shifting with reasoning, arithmetic and reading have almost exclusively been studied in clinical groups.

The goal of the present study was twofold. First, we wanted to examine whether the three EFs inhibition, shifting, and updating were distinguishable as separate EFs in a non-clinical sample of children aged 9 to 12. Second, we wanted to investigate the individual EFs' relationships with reasoning, reading, and arithmetic.

In the current study, we combined the two ways of dealing with the task impurity problem, i.e., we used control tasks in the context of CFA. The control tasks allowed us to control for variance attributable to non-executive task demands. CFA was then used to differentiate the non-executive common variance from the executive common variance. By combining control tasks and CFA, variance in performance on executive tasks that remains unexplained after accounting for the variance in performance on the control tasks, can be attributed more confidently to the EFs under study.

Tasks that require the rapid naming of stimuli have proven useful as measures of both inhibition and shifting in previous studies (Anderson et al., 2001; Bull & Scerif, 2001; van der Sluis, et al., 2004). These tasks can be viewed as variations of the Stroop Color/Word task. The Stroop task is a well established, easy to administer, measure of inhibition that has been used for over fifty years (see MacLeod, 1991, for a review). In a previous study (van der Sluis et al., 2004), we used the same naming-format to create a measure of shifting ability. The resulting task resembled the Contingency Naming Task, which has been used by various authors as an indicator of shifting ability (e.g., Anderson et al., 2001; Taylor and colleagues, 1987, 1990). In these naming-based shifting tasks, stimuli are presented in pairs, and external cues determine which of the stimuli is to be named.

In the present study, we used the Stroop and adaptations thereof as indicators of both inhibitory ability and shifting ability. All these tasks consisted of a control task, and a manipulated task that only differed from the control task in its additional appeal to an EF. Such speeded tasks are however not practicable as measures of updating ability, given that updating ability is most apparent in an increase in response errors, and not in a decrease in speed. We therefore did not force updating ability into the Stroop-format, but used adaptations of the updating tasks Keep Track and Letter Memory, as used by Miyake et al. (2000) in their adult sample. Although these tasks do not have simple control conditions, they too do require the naming of stimuli. The effect of this non-executive requirement in the updating tasks could thus be controlled for through the naming-control tasks that accompanied the inhibition and shifting tasks.

Method

Participants

Parental consent was obtained for 172 children (84 boys, and 88 girls) to participate in this study. The children attended grade 4 (n = 100) and grade 5 (n = 72) of six primary schools for regular education in the urban regions of Amsterdam and Amstelveen (the Netherlands). Mean age of the sample was 128.08 months (*SD* = 8.65).

Tasks

All children were tested for inhibition, shifting, and updating ability, for verbal and non-verbal reasoning, and for arithmetical and reading ability. Twelve EF tasks were administered: 5 inhibition tasks, 4 shifting tasks, and 3 updating tasks. For all three executive functions, we selected renowned measures, or constructed adaptations thereof to make them more apt for children. Of the 12 EF tasks, 8 had a rapid naming format (3 shifting tasks, and 5 inhibition tasks), 1 task was speeded but did not require naming (a shifting task), and 3 were non-speeded but did require the naming of stimuli (3 updating tasks).

All 8 EF tasks with a rapid naming format had a similar structure. For these tasks, simple rapid naming tasks were administered as control tasks. Manipulated rapid naming tasks did not differ from these simple tasks in anything but the requirement to inhibit or shift. The part of the manipulated tasks that could not be explained by performance on the control tasks, was taken as indicative of shifting or inhibitory ability.

All control and manipulated naming tasks consisted of a card with 40 stimuli (5 rows of 8 stimuli each). In all naming tasks, (combinations of) 4 different stimuli were used, which were presented in random order and appeared approximately equally often. Subjects were instructed to name the stimuli as fast as they could without making errors. For both the control and the experimental naming tasks, scores consisted of the number of items named per second (i.e., 40 divided by the time needed to complete the task).

Example items preceded all tasks that required rapid naming. The examples were used to familiarize the subjects with the task requirements. All examples consisted of 2 rows of 8 stimuli. The experimenter read the instructions aloud, named the first 4 stimuli of the example, and then asked the child to complete the example. If children were noticeably in doubt about the instructions, the example was presented again.

All control tasks, inhibition tasks, and shifting tasks, are illustrated in the Figures 1, 2, and 3.

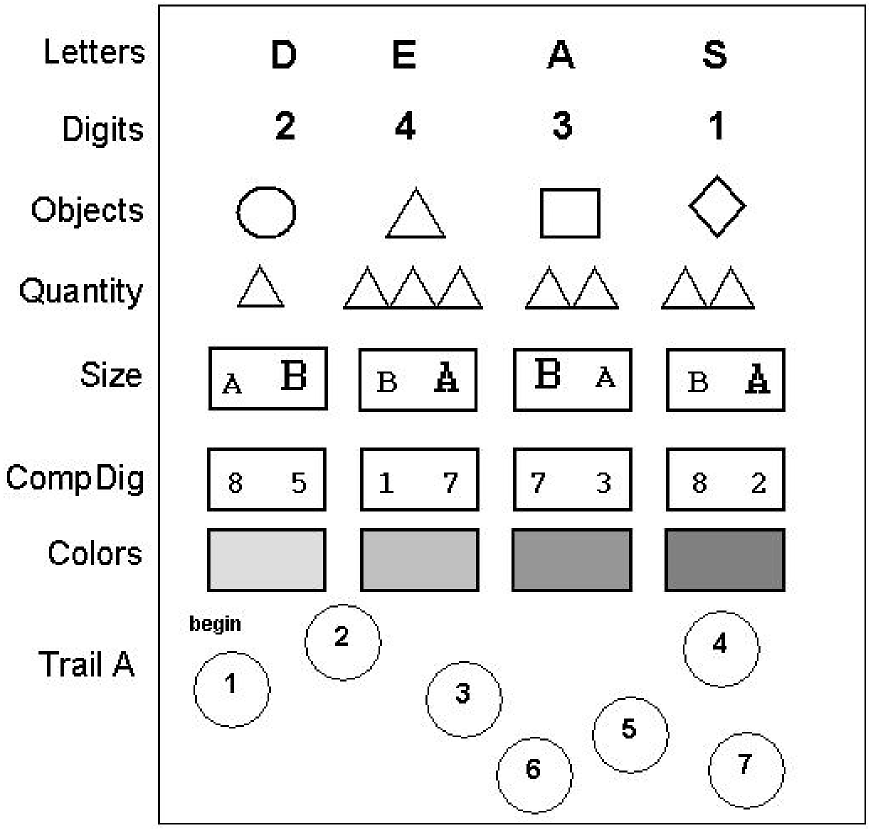

Figure 1. Examples of all control tasks.

Inhibition

Five measures of inhibition were administered, which were all derived from simple regular naming tasks. Extra time required to finish these inhibition-loaded tasks, in comparison to the control tasks, was attributed to the additional inhibition requirement, and thus considered indicative of inhibitory ability.

Quantity Inhibition. The Quantity Naming task was derived from Bull and Scerif (2001), and was used previously by van der Sluis et al. (2004). The Quantity control task consisted of series of small triangles ranging in number between 1 to 4. Subjects were required to name the number of triangles in a series. In the manipulated version, the Quantity-I task, subjects were presented with series of digits instead of triangles. Again, they had to name the number of stimuli within the series. For example, if the series '444' was presented, the correct answer was '3'. So, the numerical denotation represented by the digits had to be inhibited in favor of the quantity of digits.

Stroop. The Stroop Color-Word test (Stroop, 1935) was used, and slightly adjusted, so that it was similar in format to the other EF naming tasks (i.e., 5 x 8 stimuli, 2 practice rows, etc.). The original Stroop Color-Word Test consists of three subtests; a card with words to be read, a card with colors to be named, and a card with color-words printed in incongruent ink colors. For this last card, subjects are to name the ink color, and have to suppress the tendency to read the color words. The main dependent variable in the Stroop task is the difference in naming speed between the color naming card, and the color-word naming card. We therefore omitted the word-card in this study. The color control task used here (Color), included colored patches of yellow, red, green, and blue. In the manipulated color task (the original color-word task, hereafter denoted as Stroop-I), the color-words 'red', 'blue', 'green', and 'yellow' were printed in incongruent ink colors (red, blue, green, and yellow).

Physical Size Inhibition. This task, and the following task, were derived from Butterworth (1999). In the control task Size, the letters A and B were presented in pairs. Each pair was enclosed by a rectangle so that pairs were clearly separated from other pairs. One of the letters of the pair was printed in a large font (Courier 28), the other in a smaller font (Courier 20). Subjects were instructed to name the larger letter of a pair. In the manipulated version, SizePhys-I, outlined pairs of digits were presented of which one was printed in the large font, and one in the smaller font. Subjects had to name the *physically* larger digit of the pairs, which was always the numerically smallest, and thus had to neglect the numerical denotation of the digits.

Numerical Size Inhibition. In the Compare Digits control task (CompDig), pairs of single digits (ranging between 1 and 9) were presented, again enclosed in rectangles. Subjects were instructed to name the numerically largest digit of a pair. In the manipulated version, SizeNum-I, one of the digits was printed in the large font, and one in the smaller font. Subjects had to name the *numerically* largest digit of a pair, which was always the physically smallest. That is, they had to ignore the larger, more prepotent digit in favor of the smaller one.

Object Inhibition. The Objects control task included the geometrical figures circle, square, triangle, and diamond, which were printed in a heavy, black line. In the manipulated version, Objects-I, the same four geometrical objects were presented but now an additional small object was placed in varying positions within the larger object. These smaller objects were printed in a light, grey line. Subjects were instructed to name the smaller, less obtrusive object. That is, they had to neglect the larger, prepotent figure in favor of the smaller, less noticeable one. A slightly different version of the Object Inhibition task was previously used by van der Sluis et al. (2004). In that study, the smaller objects were printed in the same heavy black line as the larger objects. We adjusted the task slightly for the present study in an attempt to enhance the interference effect.

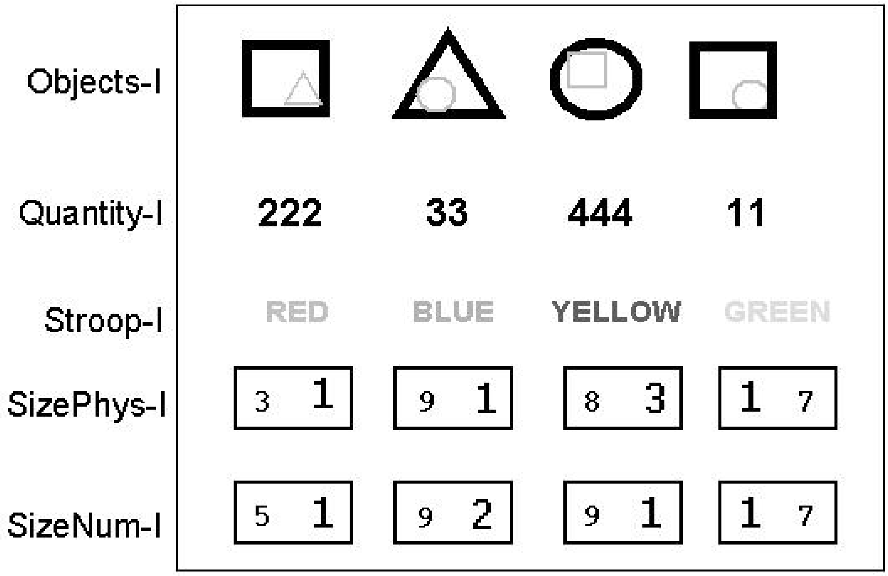

Figure 2. Examples of the inhibition tasks. For the Stroop-I task, the different shades of grey illustrate the different ink colors.

Shifting

Four tasks were used as indicators of shifting ability. Three tasks were variations of the regular rapid naming tasks. Extra time required to finish the shifting-loaded tasks, in comparison to the control tasks, was attributed to the additional shifting requirement, and thus considered a measure of shifting ability.

Objects Shifting. Like the Symbol Shifting task, which is described below, the Objects Shifting task can be considered a derivative of the Contingency Naming Test (CNT, Taylor and colleagues, 1987, 1990). In the CNT, naming is rule-based. The CNT consists of series of geometrical shapes in shapes (inside and outside shapes), and, depending on the similarity of the shapes, subjects are required to name the inside shape, or the color of the shapes. Yet, when a reversed arrow accompanies the shapes, the subjects are required to reverse the naming-rules.

The Objects Shifting task used here was previously used by van der Sluis et al. (2004). There were two control conditions for this task: the same Objects naming control task as used in the Objects Inhibition version, and a digit naming control task, Digits. The Digits task included the numbers 1, 2, 3, and 4. In the manipulated shifting version, Objects-S, the four geometrical objects were presented but now a digit (1 to 4) was placed in the centre of the objects. Depending on the color of the stimulus, subjects were to name either the object or the digit. When the stimulus was blue, the object had to be named, when yellow, the digit had to be named.

Symbol Shifting. The Symbol Shifting task had two control tasks: the Digits naming task as described before, and the Letters task, which included the letters A, E, S, and D. In the manipulated version, Symbols-S, a letter and a digit were presented in pairs (again enclosed by a rectangle so that pairs were clearly separate). Subjects were either to name the letter or the digit, depending on the color of the stimulus. When the pair was printed in blue, the letter had to be named, when printed in yellow, the digit had to be named.

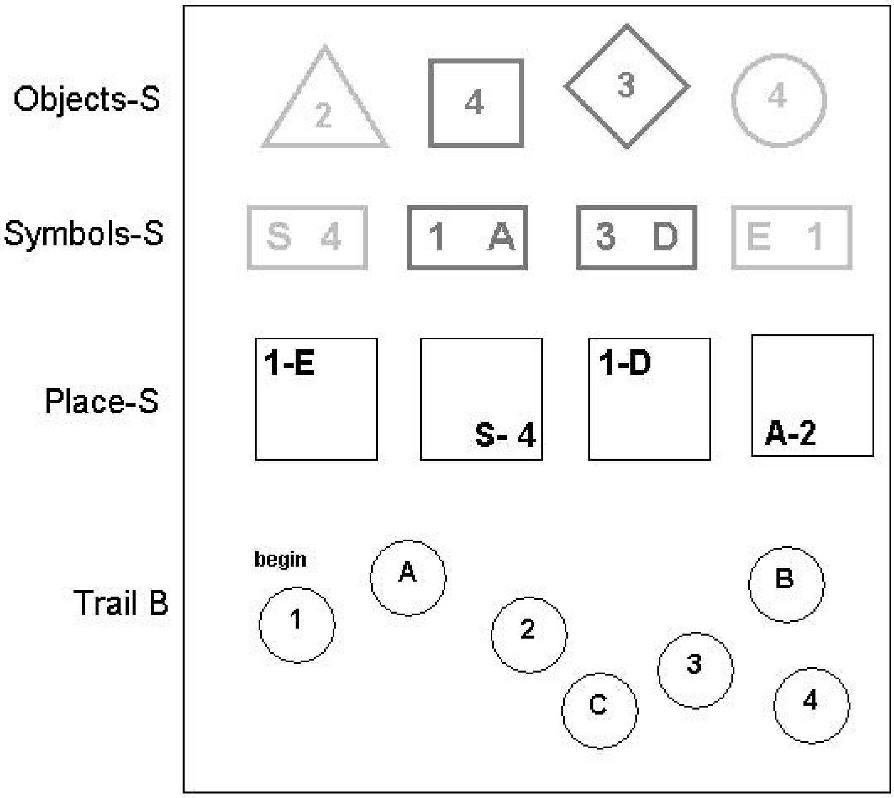

Figure 3. Examples of the shifting tasks. For Objects-S and Symbols-S light grey objects should be considered yellow, darker grey objects should be considered blue.

Place Shifting. Like the Symbols-S task, Place-S was a manipulation of the control tasks Letters and Digits. Again, pairs of letters and digits were presented. The Place-S task was adapted from the Numbers-Letters task as used by Rogers and Monsell (1995), and Miyake et al. (2000) in studies with adult participants. In its original form, the subjects are presented with pairs of letters and digits on a computer screen. Depending on the location of the pair, subjects are required to indicate whether a digit is odd or even, or whether a letter is a consonant or a vowel. Because these distinctions (odd or even, vowel or consonant) may be too hard for children, we changed the rules to naming either the letter or the digit, conditional on the location.

In the Place-S task, the pairs were placed in one of the corners of a square. Subjects were to name either the letter or the digit, depending on the position of the pair in the square. Subjects were to name the letter when the pair was printed in one of the top corners, and they had to name the digit when the pair was printed in one of the bottom corners.

Making Trails Task. This task was part of the paper and pencil version of the Making Trails task that was previously used by, for example, McLean and Hitch (1999). The control task Trail A is the only control tasks that does not require naming, although it is speeded, like the other control tasks. Subjects were presented with a card containing 22 numbered circles. The instructions were to start at the circle carrying the number '1', and then connect the circles with a pencil in ascending order (i.e., 1-2-3-4-5 etc.) as quickly as possible. In the shifting variation, Trail B, subjects were again presented with a card, which contained 22 circles. Now, the circles carried either a digit or a letter. Subjects were to start at the circle containing '1', and make a trail, alternately connecting digits and letters in ascending order (i.e., 1-A-2-B-3-C, etc.) as quickly as possible. For both trail making versions, the test score consisted of the number of circles connected per second. To familiarize subjects with the trail-making format, both Trail A and Trail B were preceded by an example trail of 8 circles.

Updating

Three tasks were used as indicators of updating ability. All three tasks were adaptations of tasks used by Miyake et al. (2000), who in turn adapted their tasks from Morris and Jones (1990), and Yntema (1963).

Keep Track. In the Keep Track task (Ktrack-U), subjects were presented with 8 series of 10 cards. On each card, a symbols or picture was shown that belonged to one of the five following categories: Letters (A, E, S, and, D), Digits (1, 2, 3, and 4), Objects (circle, square, triangle, and diamond), Animals (cat, dog, bird, and fish), or Vehicles (car, bike, train, and airplane). Before the start of each series, the experimenter designated the 3 or 4 'target categories' for that specific series. Each series included 1, 2 or 3 cards from these target categories, supplemented by cards from the other categories. Subjects were instructed to name all pictures in the series, and to keep track of the target categories. At the end of a series, they were asked to name the last picture that they had seen of each of the target categories. For example, when the target categories were letters and animals, and the following series was presented: 'E, cat, bike, square, airplane, fish, triangle, A, 1, train', the correct answer was 'A and fish' (the order of recall was free). Of the 8 series, the first 4 required keeping track of 3 target categories, and the last 4 required keeping track of 4 target categories. Thus, in total, 28 pictures had to be recalled. The test score was the proportion of pictures recalled correctly.

In the original task, as described by Miyake et al. (2000), subjects were presented with 6 series consisting of 15 words (not pictures), with either 4 or 5 target categories. The categories were rather abstract (e.g., metals, distances, countries). We thus simplified the task somewhat to make it more appropriate for younger participants.

Before the beginning of the task, participants were shown all 5 target categories, and the 4 symbols/pictures in each category, to ensure that they were familiar with the depicted objects, and knew to which category they belonged. To familiarize the children with the task, two practice series of 6 pictures and 2 target categories were presented. All symbols/pictures were black and white, and printed in a landscape, A4 size booklet. Within a series, the experimenter turned the pages at a rate of approximately 2 seconds per page. As a reminder, the target categories remained visible in the left bottom corner of each page within a series.

Letter Memory. In the Letter Memory task (Letters-U), subjects were presented with series of letters, which varied in length from 3, 5, 7, to 9 letters. Subjects were asked to constantly recall the last three letters presented to them. That is, they were instructed to update throughout a series, continually adding the last presented letter to a cluster and dropping the earlier fourth letter. For example, when a series included the following letters 'R, B, K, A, G', subjects were required to respond 'R', 'RB', 'RBK', 'BKA', and 'KAG'. The length of the series varied unpredictably for the subjects.

In the original Letter Memory task as described by Miyake et al. (2000), 12 series were presented, varying in length from 5, 7, 9, to 11, and subjects were required to recall the last 4 letters. We thus simplified the task somewhat to make it more appropriate for children.

The test consisted of 8 series total (2 series of each length), resulting in 48 clusters of letters to be recalled. The proportion of clusters recalled correctly, was used as the test score. Before the test began, three practice series (2 of length 3, 1 of length 5) were presented to illustrate the task. The letters used in the Letters-U task were A, O, H, K, B, G, R, T, and S. The letters were printed in Arial 120 in a landscape, A4 size booklet. Within a series, experimenters turned the pages at a rate of approximately 2 seconds per page.

Digit Memory. The Digit Memory task (Digits-U) was a numerical version of the Letters-U task. Now, series (length 3, 5, 7, or 9) of digits (1 to 9) were presented, and children were again instructed to update throughout a series. Again 48 clusters of digits had to be recalled, and the proportion of clusters recalled correctly was used as the test score. The digits were printed in Arial 120 in a landscape, A4 size booklet, and within a series, experimenters turned the pages at a rate of 2 seconds per page. Like with Letters-U, three practice series were presented (2 series of 3 digits, and 1 series of 5 digits).

Reasoning, arithmetic, and reading

Four standardized achievement tests were administered: two for reasoning ability (verbal and non-verbal), one for arithmetic ability, and one for reading ability.

Verbal reasoning. The Verbal Analogies subtest of the RAKIT, a Dutch intelligence test for children (Bleichrodt, Drenth, Zaal, & Resing, 1987), was used to assess verbal reasoning ability. This test consists of 30 multiple-choice items of the format 'A is to B, as C is to ?', and children were required to select the correct answer from four answer options. Pictures illustrate all words in the test. Completion of the test took 30 minutes at most.

Non-verbal reasoning. The Raven Standard Progressive Matrices (Raven, Court, & Raven, 1979) was used as a measure of non-verbal reasoning ability. The Raven consists of sixty series of abstract patterns. From each pattern, a piece is missing. Children were required to select the missing piece from a set of 6 to 8 answer options. Completion of this test took 45 minutes at most.

Reading. The One Minute Reading Test (OMRT, Brus & Voeten, 1995) was used as a measure for word reading efficiency, or fluency. This test is used as a standard measure of early reading acquisition in Dutch education. The OMRT consists of a list of 116 unrelated words of increasing difficulty. Children were instructed to read as many words as they can in one minute without making errors. The test score consisted of the number of words read correctly in one minute.

Arithmetic. As a measure of arithmetic ability, the Arithmetic Tempo Test (ATT, De Vos, 1992) was administered. Children were presented with three sets of 50 arithmetic problems. Each set consists of a series of homogeneous problems. The first set requires addition, the second subtraction, and the third multiplication. All problems consist of 2 numbers, both ranging from 0 to 99. Within a set, problem difficulty increases. About the first 20 problems cover arithmetic facts. If arithmetic ability is automatized, these problems thus appeal mainly to arithmetic fact retrieval. Per set, subjects were instructed to solve as many problems as possible within three minutes. The test score consisted of the mean number of problems solved correctly over the three subtests.

Procedure

Administration of the reasoning, reading and arithmetic tasks was distributed over two days. The first day, children were tested group-wise for arithmetic ability and verbal reasoning ability, and approximately half of the children were individually tested for reading ability. On the second day, the test for non-verbal reasoning was administered group-wise, and the remaining children were tested for reading ability.

After the administration of the achievement tests, all children were individually tested in three sessions lasting approximately 25 minutes each. During each session, one updating task was administered, supplemented with 7 naming tasks (control or manipulated). The sessions took place in a period of 3 days to 3 weeks. To prevent order effects, the nine control tasks and 12 experimental tasks were presented in three different orders, which were composed such that tasks demands were least likely to interfere. Graduate students, who were trained prior to testing, administered the tests.

Results

The results of the present study are presented in four sections. In the first section, descriptive statistics of all measures are presented. In the second section, results of ANOVA's for repeated measure are reported, which were carried out to test the effectiveness of the inhibition and shifting manipulations. The results of the confirmatory factor analysis (CFA) using LISREL 8.50 (Jöreskog & Sörbom, 2001) are presented in the third section. In that section, the latent factors Inhibition, Shifting, and Updating are related to the observed variables. The question whether the three executive functions are detectable, is central to this section. In the fourth section, results of structural equation modeling (SEM) are presented. Here, the latent factors for the executive functions are related to reading and arithmetic ability, and verbal and non-verbal reasoning ability.

Descriptive Statistics

Of the 172 children tested, 2 had missing values on one measure (1 on Symbols-S, and 1 on Letters). For the naming tasks, scores were recoded as missing if 25 % or more of the to-be-named stimuli were named incorrectly. This was done because naming time can only be considered a valid score if the number of naming errors is limited. Five children displayed more than 25 % incorrect answers on one task: 3 on Place-S, 1 on SizePhys-I, and 1 on

SizeNum-I. One child had more than 25 % incorrect answers on both Place-S and Symbols-S. Finally, nine scores were recoded as missing because these were outlying. Scores were considered outlying if they were more than 3 *SD*s

Table 1
Descriptive statistics for 2 arithmetic tasks, 2 reasoning tasks, 9 control tasks, 5 inhibition tasks, 4 shifting tasks, and 3 updating tasks

Test	*M*	*SD*	*Skew.*	*Kurt.*	*n*
Reasoning					
Non-verbal	42.36	7.07	-.530	.203	171
Verbal	24.66	3.62	-.867	.362	171
Arithmetic	35.98	6.30	-.135	-.261	172
Reading	65.81	12.67	-.002	.366	172
Control tasks					
Letters	42.86	7.66	.058	.346	171
Digits	45.42	9.05	.281	.482	172
Objects	20.97	4.17	.253	.133	171
Quantity	32.73	5.48	.374	-.120	172
Color	32.94	5.85	-.100	.293	172
Size	34.84	6.44	.129	.033	172
Compdig	24.22	3.92	.150	.331	172
Trail A	19.55	6.90	.563	-.289	171
Inhibition					
Quantity-I	21.86	3.91	.414	.163	171
Objects-I	19.52	4.06	.211	.203	172
Stroop-I	19.56	3.99	.220	-.065	171
SizePhys-I	37.16	7.12	.277	.046	171
SizeNum-I	23.27	5.37	.786	.526	171
Shifting					
Objects-S	17.10	3.33	.121	-.285	172
Place-S	16.13	3.45	.334	.027	168
Symbols-S	16.88	3.28	.436	.065	170
Trail B	9.79	3.23	.505	-.008	169
Updating					
Ktrack-U	70.34	14.63	.163	-.614	172
Letters-U	94.34	6.97	-1.678	2.599	172
Digits-U	96.19	5.36	-2.103	5.152	172

from the mean. Taken together, this resulted in 16 missing scores, which is less than .5 % of the data.

The descriptive statistics for all measures are presented in Table 1. Note that for all speeded tasks, lower scores represent slower performance. Table 2 contains the correlations between all measures in the study. Note that the correlation matrix is based on all 172 cases, despite the missing data. Full Information Maximum Likelihood (FIML) estimation was used to calculate the full information covariance matrix from the raw data. The correlation matrix in Table 2 is based on this covariance matrix. This covariance matrix was used in subsequent model fitting in the third and fourth section.

The correlations in Table 2 are of interest for three reasons. First, all tasks that required the naming of stimuli, either with or without additional executive requirements, appeared considerably interrelated. These intercorrelations were of course due to the communality in measuring method, i.e., naming speed. However, one would expect each manipulated task to be especially related to its control counterpart. This appeared not always to be the case. The correlations of several manipulated tasks with other control tasks were also considerable, and sometimes within the same range as the correlations with their specific control counterparts. For instance, the Quantity-I task was considerably related to the Quantity control task (.61), but also to the control tasks that required the comparison of digits (CompDig, .63), and the naming of objects (Objects, .50). Likewise, the Stroop-I task was considerably related to its own control task Color (.60), but also to the Object naming control task (.63), and the Quantity naming control task (.58). For the Shifting tasks, this tendency of manipulated tasks to be correlated within the same range with other control tasks as with their own counterparts was also present, although somewhat less pronounced.

Second, Table 2 shows that the correlations between the control tasks and the scholastic measures on the one hand, and the correlations between the manipulated tasks and the scholastic measures on the other hand, did not differ much. The similarity of these correlations could mean that, even if the executive versions of the naming tasks are in themselves respectable predictors of the scholastic abilities, they may not add much to the prediction when performance on the control tasks is taken into account.

Third, Table 2 shows that the *within*-trait correlations, i.e., the correlations between the Inhibition tasks, and the correlations between the Shifting tasks, were approximately of the same order as the between-trait correlations. That is, the correlation matrix did not show much evidence of divergent validity (Campbell & Fiske, 1959; Marsh, 1989; Marsh & Bailey, 1991).

Table 2

Correlation between 1 reading test, 1 arithmetic test, 1 verbal reasoning test, 1 non-verbal reasoning test, 8 control tasks, 5 inhibition tasks, 4 shifting tasks, and 3 updating tasks (n=172)

	Scholastic				Control tasks								Inhibition					Shifting				Updating		
Reading	1.000																							
ARithmetic	.445	1.000																						
VerbalReas.	.141	.198	1.000																					
Non-verbal Reas.	.266	.300	.470	1.000																				
Letters	.446	.241	.056	.002	1.000																			
Digits	.414	.225	-.105	-.111	.663	1.000																		
Objects	.380	.381	.163	.095	.432	.367	1.000																	
Quantity	.433	.465	.198	.189	.562	.495	.597	1.000																
Color	.439	.367	.128	.149	.497	.493	.556	.570	1.000															
Trail A	.277	.337	.164	.167	.325	.309	.287	.456	.351	1.000														
Size	.357	.213	.185	.121	.590	.462	.446	.609	.435	.388	1.000													
Compdig	.281	.444	.151	.146	.482	.447	.442	.568	.416	.430	.582	1.000												
Quantity-I	.331	.567	.168	.201	.485	.442	.498	.614	.445	.363	.449	.628	1.000											
Objects-I	.263	.248	.060	.028	.368	.324	.607	.478	.457	.201	.342	.362	.409	1.000										
Stroop-I	.446	.455	.137	.219	.479	.447	.629	.583	.604	.343	.508	.490	.601	.435	1.000									
SizePhys-I	.390	.281	.218	.100	.574	.566	.377	.592	.585	.409	.687	.520	.473	.385	.464	1.000								
SizeNum-I	.264	.315	.193	.053	.441	.337	.404	.500	.351	.383	.471	.519	.437	.256	.372	.510	1.000							
Objects-S	.355	.408	.155	.099	.419	.458	.549	.577	.477	.449	.464	.445	.573	.419	.577	.507	.409	1.000						
Place-S	.244	.393	.224	.181	.376	.290	.370	.451	.450	.288	.416	.356	.439	.259	.499	.468	.367	.475	1.000					
Symbols-S	.188	.316	.186	.245	.284	.176	.382	.346	.344	.306	.386	.402	.390	.393	.452	.388	.423	.496	.568	1.000				
Trail B	.188	.387	.240	.339	.140	.050	.146	.210	.239	.532	.202	.279	.252	.173	.267	.256	.182	.276	.318	.385	1.000			
Ktrack-U	.236	.208	.351	.269	.109	.058	.035	.179	.151	.187	.083	.186	.177	-.056	.056	.174	.182	.271	.229	.157	.273	1.000		
Letters-U	.281	.210	.157	.231	.097	.073	.189	.201	.177	.255	.050	.009	.122	.050	.228	.136	.138	.248	.218	.108	.271	.387	1.000	
Digits-U	.208	.168	.122	.266	.053	-.040	.102	.091	.131	.225	.037	.019	.062	-.005	.188	.050	.061	.100	.048	.105	.298	.249	.433	1.000

Effectiveness of the Manipulations

If the inhibition and shifting manipulations had been effective, this would first of all become visible in significantly slower performance on the manipulated tasks, in comparison to the control tasks. To examine whether the means on the manipulated tasks were lower than the means on the control tasks, ANOVA's for repeated measures were performed. In each of these analyses, a control task and a manipulated task constituted the within-subjects factor. For the manipulated tasks with two control counterparts, two ANOVA's for repeated measures were performed, so that the means of both control tasks were compared separately to the mean of the manipulated task.

Visual inspection of the means of the tasks (Table 1), showed that the mean of the manipulated task SizePhys-I was *higher* than the mean of its control task Size. Naming the physically largest letter (Size) thus took more time than naming the physically largest number (SizePhys-I), even though this number was always the numerically smallest (i.e. size and denotation were supposed to interfere). The manipulation thus seemed to have had a small facilitating, rather than interfering effect. As this makes SizePhys-I unsuitable as a measure of Inhibition, we excluded this task, and its specific control task Size, from further analysis.

An overview of the results of the ANOVA's for repeated measures is presented in Table 3. As the results in Table 3 show, all repeated measures analyses for the inhibition tasks were significant, meaning that all four inhibition manipulations had slowed down naming speed. Yet, the size of the effects of the manipulations differed considerably between the tasks. The inhibition manipulation in the Objects-I task (η^2 = .14) had slowed down naming speed to a lesser extent than the manipulations in Quantity-I (η^2 =.86), and Stroop-I (η^2 =.89). Also, the mean naming speed of SizeNum-I was much lower than the mean naming speed of its control task Digits (η^2 =.86), but the difference with the control tasks CompDig was less striking (η^2 =.04), although still significant.

The results in Table 3 also show that the additional shifting requirement had, in all four shifting tasks, resulted in a significant extension of the time needed to finish the tasks, compared to the time needed to finish the respective control tasks. All effect sizes were large, ranging between .54 and .93.

Summarizing, we can conclude that in all four Shifting tasks, the manipulation had resulted in significantly slower naming, i.e., less items were named per second. Apart from SizePhys-I, all Inhibition manipulations had resulted in significant prolongation of the naming time as well, although the size of the effects differed greatly between manipulations, and was most striking for Quantity-I and Stroop-I.

Table 3
Results of the repeated measures analyses for the five Inhibition and four Shifting tasks

Effect	*F*	*df*	*p*	η^2
Inhibition				
Quantity vs. Quantity-I	1065.73	1,170	< .001	.86
Objects vs. Objects-I	28.31	1,170	< .001	.14
Color vs. Stroop-I	1390.53	1,170	< .001	.89
Digits vs. SizeNum-I	1080.32	1,170	< .001	.86
Compdig vs. SizeNum-I	6.62	1,170	< .01	.04
Shifting				
Trail A vs. Trail B	461.77	1,167	< .001	.73
Digits vs. Objects-S	2109.71	1,171	< .001	.93
Objects vs. Objects-S	195.27	1,170	< .001	.54
Digits vs. Place-S	1896.31	1,167	< .001	.92
Letters vs. Place-s	2303.18	1,166	< .001	.93
Digits vs. Symbols-S	1718.31	1,169	< .001	.91
Letters vs. Symbols-s	2054.18	1,168	< .001	.92

Structure of Executive Functions

The repeated measures analyses in the previous section have shown that the control tasks and the manipulated tasks differed in their means. Yet, it remains to be seen whether Inhibition, Shifting, and Updating can be distinguished as separate latent factors, and as such account for variance *in addition to* the variance that is explained by the control tasks. By modeling the control tasks along with the executive tasks, the significance of the executive factors can be established in the actual presence of the control tasks.

As all control tasks in the present study were naming tasks, we modeled the control tasks as indicators of one general Naming factor. To begin with, the manipulated tasks were also modeled as indicators of this general Naming factor. As the three updating tasks also required the naming of stimuli, these tasks were modeled as indicators of Naming as well. Specific relations between manipulated tasks and their specific control counterparts could subsequently be modeled to compensate for additional task specificities, i.e., variability due to the specific type of stimulus that had to be named in certain manipulated tasks. After modeling these non-executive task requirements, we examined whether additional factors for Inhibition, Shifting, and Updating were actually necessary in order to arrive at a satisfactory description of the interrelations among the tasks. This approach has been proposed, and used in studies on the structure of general intelligence (e.g., Gustafsson, 1992; Gustafsson and Undheim, 1992), and was previously used in the EF context by Oberauer et al. (2003).

To evaluate the fit of the ensuing models to the data, we used the following fit indices (Bentler, 1990; Bollen & Long, 1993; Jöreskog, 1993; Schermelleh-Engel, Moosbrugger, & Müller, 2003): the χ^2 statistic, the root mean square error of approximation (RMSEA), the comparative fit index (CFI), and the incremental fit index (IFI). The χ^2 statistic is considered a measure of (badness of) fit. A large χ^2 value, relative to the number of degrees of freedom, indicates that the specified model does not adequately account for the observed covariance matrix. As a rule of thumb, χ^2 values smaller than twice the degrees of freedom indicate a good fit, and χ^2 values between 2 and 3 times the degrees of freedom indicate adequate fit. The RMSEA is a measure of the error of approximation of the covariance and mean structures of the specified model to the observed covariance and mean structures in the population. As a rule of thumb, Browne and Cudeck (1993) suggested that a RSMEA of .05 or less is indicative of a good approximation, a value between .05 and .07 is indicative of reasonable approximation, and values greater than .08 indicate poor approximation. We also considered the CFI, as this index takes sample size into account, and the IFI, which considers both the parsimony of a model, and sample size. Coefficient values for the CFI and the IFI range from zero to 1.00, and values > .90 are usually taken as indicative of adequate model fit.

The above four fit indices are informative about the general fit of the model to the data. In addition, for every fixed parameter in the model, the LISREL program provides a Modification Index (MI), the value of which represents the expected drop in overall χ^2 if the parameter is to be freely estimated. The MI's thus provide information on local misspecifications in the model. So, in addition to the measures of general fit, we used modification indices (MI) to assess local misfit. The fit of nested models can be compared by subtracting the χ^2 value of a less restrained model with more free parameters from the χ^2 value of a more restricted model with fewer free parameters. If the resulting χ^2-difference is significant, the less restrained model provides the better fit. Thus, one can test whether freeing parameters results in a significant decrease in overall χ^2. When testing for significance, we used a conservative criterion level of $\alpha = .01$, which was considered reasonable given the complexity of the models, and the number of tests, which are to follow.

First we fitted a 1-factor model to the 7 naming control tasks[7]. The fit indices of this model, Model N_1, are shown in Table 4. The poor fit of Model N_1 seemed mainly due to an additional relation between Letter and Digit naming, which was not accounted for by the general Naming factor. Because these two tasks are the only naming tasks that require the simple naming of alpha-numeric characters, this relation makes sense. We included a relation between Letters and Digits by allowing their residual terms to correlate in Model N_2. This model fitted well, and the χ^2 difference test, comparing Model N_2 to Model N_1, proved significant ($\chi^2_{diff}(1) = 27.55$, $p < .001$), suggesting that the fit of the model had improved significantly. The good fit of this single common factor model can be taken to mean that all control tasks appeal to the same underlying ability.

With the control tasks in place, we first examined whether the scores on the naming tasks that were designed to appeal to the executive function of Shifting, could be taken as indicative of more than Naming speed alone.

Model N_2 was taken as point of departure. We first modeled the shifting tasks as four additional indicators for naming speed by loading them on the Naming factor (Model S_1). This 1-factor model fitted the data poorly (see Table 4): the RMSEA was too high (.11), and the CFI (.87) and the IFI (.88) were too low. The loadings of all four shifting tasks on the Naming factor were however significant according to χ^2 difference tests, which implies that naming speed did account for a significant amount of the variance in the shifting measures.

Before adding an additional Shifting factor, we first checked whether the model could be improved by relaxing specific relations between the manipulated tasks and their control counterparts, which were not accounted for by the general Naming factor. It is conceivable that pairs of control and manipulated tasks share additional variance above general Naming. This could, for instance, be due to the communality of the to-be-named stimuli used in both tests[8]. Correlations between the residual terms of a manipulated task and its control task may be introduced to deal with these specific relations. We therefore examined the Modification Indices (MI's) of Model S_1. The MI's showed that the fit of the model would improve if the residual terms of Trail A and Trail B were correlated. This additional relation between Trail A and Trail B is further comprehensible since this was the only pair of tasks in the model that was speeded but did not require naming.

In Model S_2, this additional relation between Trail A and Trail B was included. Although Model S_2 fitted the data better than Model S_1 ($\chi^2_{diff}(1) = 35.96$, $p < .001$), the fit was still not satisfactory. No other specific relations

---

[7] Note that Trail A is not actually a naming task. Yet, we chose to incorporate Trail A in this general factor because Trail A shares the speed requirement with the other control tasks. Inclusion of Trail A as an indicator of the Naming factor would result in the most economical description of the control data.

[8] If we take the Stroop task as example, the specific requirement to name colors, rather than quantities, alpha-numeric symbols or geometrical objects, might result in specific within-pair common variance that is not explained by the common factor Naming.

between paired tasks could account for this misfit. Therefore, we introduced a specific factor for Shifting, on which all four shifting tasks were allowed to load freely.

The fit of the resulting model, Model S_3, was good. Furthermore, the loadings of the shifting tasks on the Shifting factor were significant, albeit small, meaning that all four tasks contributed to this second factor. The variance of the Shifting factor was small, yet significant, suggesting that the Shifting factor explained variance on top of the variance explained by the Naming factor. Note that, because the Naming and Shifting factors were uncorrelated, the variance that is explained by the Shifting factor can be considered additional to, and independent of, the variance already explained by the Naming factor.

In conclusion, the scores on the manipulated naming tasks that were designed to appeal to Shifting, can indeed be taken as indicative of more than Naming speed alone, and the additional variance in those four tasks could be accounted for by one factor. We will now turn to the manipulated naming tasks that were designed to measure Inhibition.

As with the shifting tasks, model N_2 was taken as point of departure, and the four Inhibition tasks were first added as indicators of Naming only. The fit of the resulting Model I_1 was not satisfactory, as the indices in Table 4 show. Especially, the RMSEA was too high (.09). However, the loading of all four inhibition tasks on the Naming factor were significant, meaning that naming speed could account for a significant amount of the variance in the inhibition measures.

Again, we first examined whether the fit of the model could be improved by relaxing specific relations between the residual terms of an inhibition task and its control counterparts. The MI's showed that three specific relations were not accounted for by the general Naming factor: the relation between Objects and Objects-I, the relation between CompDig and SizeNum-I, which are both within-pair relations, and the relation between ComDig and Quantity-I. Although ComDig is not the control counterpart of Quantity-I, we thought this relation acceptable since both tasks require the evaluation of numerical quantity. These three additional relations were incorporated in Model I_2. Model I_2 provided a more accurate description of the data than Model I_1 ($\chi^2_{diff}(3)$ = 42.40, $p < .001$). Besides, the fit indices in Table 4 show that the fit of Model I_2, in which the inhibition tasks were treated as regular naming tasks, was good.

Although the fit indices suggested that Model I_2 provided a good description of the data, we nevertheless added a common Inhibition factor to examine whether an Inhibition factor explained variance in addition to the variance explained by the general Naming factor (Model I_3). As the fit indices of the resulting Model I_3 show, the fit of Model I_3 hardly differed from the model without a common factor for Inhibition ($\chi^2_{diff}(4)$ = 9.12, p = .06). Besides, all loadings of the inhibition tasks on the Inhibition factor were insignificant and negative, as was the variance of the Inhibition factor.

In Model I_4, we abandoned the three correlated residual terms, and examined whether a second common factor could be distinguished if the control tasks Objects and CompDig were allowed to load on this factor, besides the 4 inhibition tasks. Although the overall fit of this model was reasonable, the resulting 'Inhibition' factor was not interpretable as its variance did not deviate significantly from zero, and the factor loadings were both positive and negative.

Table 4
Model fit indices

	χ^2	*df*	*p*	*RMSEA*	*CFI*	*IFI*
N_1	45.38	14	.00	.12	.93	.93
N_2	17.83	13	.16	.04	.99	.99
S_1	141.39	43	.00	.11	.87	.88
S_2	105.43	42	.00	.10	.92	.92
S_3	54.32	38	.04	.04	.98	.98
I_1	93.99	43	.00	.09	.94	.94
I_2	51.59	40	.10	.04	.99	.99
I_3	42.47	36	.21	.04	.99	.99
I_4	55.81	37	.02	.05	.98	.98
IS_1	120.26	81	.00	.05	.97	.97
ISU_1	257.26	126	.00	.08	.90	.90
ISU_2	200.66	123	.00	.05	.94	.94
ISU_3	184.24	121	.00	.05	.95	.95
$FULL_1$	287.01	181	.00	.05	.93	.94
$FULL_2$	295.11	184	.00	.05	.93	.93
$FULL_3$	264.81	181	.00	.05	.95	.95

Because the model without a specific Inhibition factor fitted the data adequately, inclusion of this factor did not improve the fit of the model, and the factor itself was not interpretable, we must conclude that a common factor for Inhibition could not be distinguished, and was not necessary for an adequate description of the present data. In the light of these findings, Model I_2 is the preferred model.

With an adequate model for the inhibition tasks in place, we modeled all control and manipulated tasks simultaneously in a 2-factor Model IS_1, with all tasks as indicators for Naming, and the four shifting tasks additionally loading on the Shifting factor. This model provided a good description of the data (see Table 4). With a model for these paired tasks in place, we included the updating tasks.

Model IS_1 was taken as point of departure. As with the shifting and inhibition tasks, the three updating tasks were first introduced as indicators of the Naming factor only, resulting in Model ISU_1. Although the three updating tasks did not have a speeded rapid naming format or naming control tasks, subjects were required to name all to-be-recalled stimuli in the updating series aloud. In this respect, naming was involved in the updating tasks. Loading the updating tasks on the general Naming factor seemed therefore justified. The fit indices in Table 4 show that Model ISU_1, in which the updating tasks were treated as ordinary naming tasks, did not provide an adequate description of the data. However, the loadings of the updating tasks on the Naming factor were all significant, meaning that naming speed could account for some of the variance in the updating tasks.

Next, we introduced a specific factor for updating ability, i.e., Updating, on which all three updating tasks were allowed to load freely. To begin with, this factor was not correlated with either the Naming factor or the Shifting factor. The fit of the resulting model, Model ISU_2, is satisfactory (as shown in Table 4). All loadings of the updating tasks on the Updating factor were significant, as was the variance of the Updating factor. Subsequent introduction of a correlation between the Updating factor and the Shifting factor did not result in significant improvement of the fit of the model ($\chi^2_{diff}(1)$ = 1.53, *ns*), so we fixed this correlation to zero in the following analyses.

With a specific factor for Updating in the model, the MI's showed that the fit of the model would improve if both Making Trails tasks, i.e., Trail A and Trail B, would be allowed to load on the Updating factor as well. These additional loadings of both Making Trails tasks on the Updating factor can be interpreted (see the Discussion for a detailed rationale), and were therefore admitted to the model. The resulting Model ISU_3 proved a better description of the data than Model ISU_2 ($\chi^2_{diff}(2)$ = 16.42, p < .001), and the overall fit of Model ISU_3 was adequate (see Table 4). Model ISU_3 is illustrated in Figure 4.

The first objective of the present study was to establish whether the executive factors Shifting, Inhibition, and Updating were detectable in children, and whether those factors could be considered separate factors, or should more accurately be viewed as one and the same factor, i.e., the Central Executive. In the present study, a common factor for Inhibition was absent, and Updating and Shifting were only correlated through their shared variance in the general Naming factor. We therefore conclude that Shifting and Updating were detectable in children as common factors, and should be considered separate executive functions.

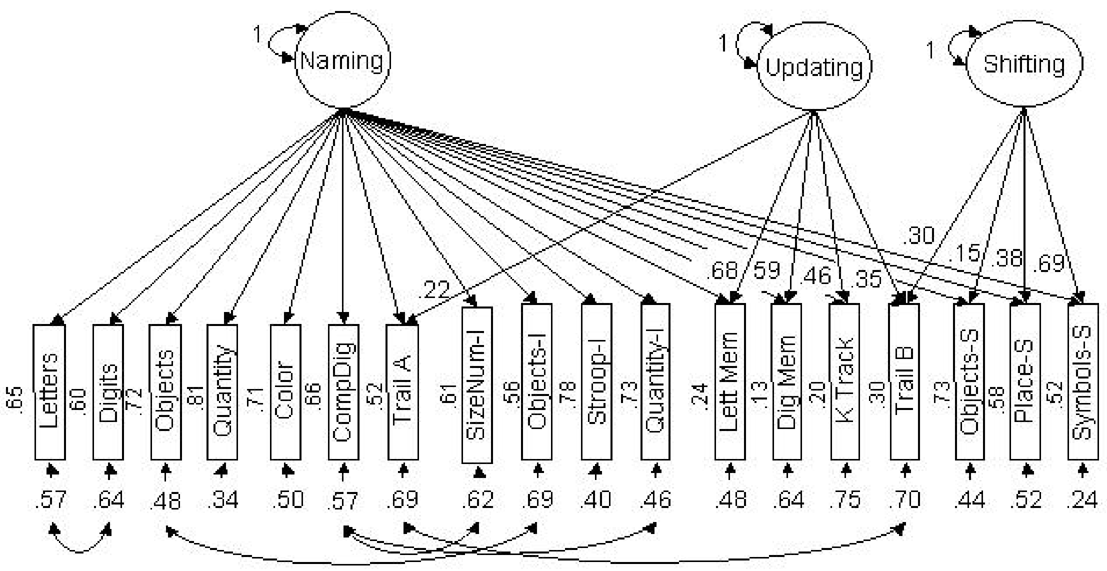

Figure 4. Model ISU_3. Loading and residual variances are completely standardized. Values for the five correlated residual variances: Letters – Digits, .27; Objects – Objects-I, .20; Trail A – Trail B, .30; CompDig – SizeNum, .16; CompDig – Quantity-I, .14.

Executive functions, reasoning, arithmetic, and reading

The second objective of the present study was to examine whether executive functions were related to verbal and non-verbal reasoning ability, reading ability, and arithmetic ability. To this end, the tasks for verbal and non-verbal reasoning, reading, and arithmetic were introduced in Model ISU_3 as four separate, but correlated 1-indicator factors, resulting in Model $Full_1$. For reasons of identification, the errors of those four factors were fixed to zero, the loading of the factors were fixed to 1, and the variances were estimated[9]. All four factors were regressed on the three common factors for Naming, Shifting, and Updating. As the indices in Table 4 show, the fit of the resulting model was reasonable.

All regression parameters between the Naming factor and the four dependent factors were significant, as were all regression parameters associated with the Updating factor. In contrast, Shifting was only significantly related to performance on the task for non-verbal reasoning ability, the Raven.

[9] Note that these four ‘dependent’ common factors are actually not latent factors as they have only 1 indicator and zero-error variance. This parameterization thus simply implies that the four indicators were directly regressed on the latent factors for Updating, Shifting, and Naming.

The relations with reading, arithmetic and verbal reasoning were all small, and fixing these parameters to zero, resulting in Model *Full₂*, did not lead to a significant decrease in model fit ($\chi^2_{diff}(3) = 8.10$, $p = .04$).

Table 5

Completely standardized factor loadings and residual variances for Model $Full_3$

	Factor loadings			Res. variances
	Naming	*Shifting*	*Updating*	
Control tasks				
Letters	.66			.57
Digits	.60			.64
Objects	.73			.47
Quantity	.81			.34
Color	.71			.49
Trail A	.52		.21	.69
CompDig	.66			.56
Shifting				
Objects-S	.73	.15		.45
Place-S	.58	.36		.54
Symbols-S	.52	.74		.18
Trail B	.30	.28	.39	-
Inhibition				
Quantity-I	.73			-
Objects-I	.56			.69
Stroop-I	.78			.40
SizeNum-I	.61			.62
Updating				
Keep Track	.20		.48	-
Letter Mem.	.24		.63	.55
Digit Mem.	.13		.60	.62
Dependant				
Arithmetic	.55		.17	-
Reading	.53		.23	-
Nonv Reasoning	.21	.17	.39	-
V Reasoning	.18		.21	-

Note. Values for the five correlated residual variances: Letters – Digits, .27; Objects – Objects-I, .20; Trail A – Trail B, .28; CompDig – SizeNum-I; .16; CompDig – Quantity-I, .12

Values for the three specific relations: Quantity-I – Arithmetic, .21; Trail B – Arithmetic, .15; Keep Track – Verbal Reasoning, .23

Inspection of the MI's showed that specific relations existed between the arithmetic test and Quantity-I and Trail B, and between the verbal reasoning task and the updating task Keep Track. The specific relations of arithmetic ability with Quantity-I and Trail B are in line with the results of a former study performed on executive functioning in children (van der Sluis et al., 2004). Inclusion of these relations was therefore considered justifiable. Because the task for verbal reasoning and the Keep Track task both require knowledge of categories and domains, this specific relation could be interpreted as well. Free estimation of these three specific relations (Model $Full_3$) resulted in significant improvement of the fit of the model ($\chi^2_{diff}(3) = 30.30$, $p < .001$). The completely standardized solution of Model $Full_3$ is presented in Tables 5 and 6.

Together, the uncorrelated factors Naming, Shifting, and Updating, and the three task specific relations, explained 34% of the variance in reading ability, 40% of the variance in arithmetic ability, 14% of the variance in verbal reasoning ability, and 22% of the variance in non-verbal reasoning ability. The partial percentages of variance explained in each dependent variable by the common factors and the three indicators, are in Table 7.

Table 6
Residual variances and partial correlations for arithmetic, reading, verbal reasoning, and non-verbal reasoning in Model $Full_3$

	Arithmetic	*Reading*	*Nonv. Reasoning*	*V. Reasoning*
Arithmetic	*.60*			
Reading	.21	*.67*		
Nonv. Reasoning	.13	.13	*.86*	
V. Reasoning	.04	-.03	.40	*.78*

Note. On the diagonal are the standardized residual variances of the four dependent factors (i.e., variance not explained by Naming, Shifting, Updating, or one of the indicators). Off-diagonals are partial correlations, i.e., correlations between these residuals.

The executive function Updating proved considerably related to non-verbal reasoning ability and reading ability, explaining 15.4% and 5.4% of the variances in these measures respectively. Although the relations with arithmetic and verbal reasoning ability were less strong, Updating still explained respectively 2.9% and 4.4% of the variance in these abilities as well. The executive function Shifting was not significantly related to arithmetic ability, reading ability, or verbal reasoning ability in this sample. Shifting was only related to non-verbal reasoning ability, and explained 3.0% of the variance in this measure. It is noteworthy that Naming was by far the best predictor of reading and arithmetic ability, explaining 28.1% and 30.3% of the variance in these variables respectively. In contrast, Naming explained only a relatively small amount of variance in verbal reasoning ability, and non-verbal reasoning ability (4.3% and 3.2 %, respectively). Beside the variance that Quantity-I and Trail B already explained through the common factors Naming and Updating, these indicators accounted for an additional 4.5% and 2.4%, respectively, of the variance in arithmetic ability through their specific relations. Likewise, performance on the Keep Track task was not only related to verbal reasoning ability through Naming and Updating, but explained an additional 5.3% of the variance in verbal reasoning ability through its specific relation.

Table 7
Percentages variance explained in reading ability, arithmetic ability, verbal reasoning and non-verbal reasoning by the common factors Naming, Shifting, and Updating, and the three tasks Quantity-I, Trail B, and Ktrack-U in Model Full$_3$

	Naming	*Shifting*	*Updating*	*Quantity-I*	*Trail B*	*Ktrack-U*	*Total variance explained*
Arithmetic	30.3		2.9	4.5	2.4		40.18
Reading	28.1		5.4				33.50
Non-verbal reasoning	3.2	3.0	15.4				21.59
Verbal reasoning	4.3		4.4			5.3	14.01

Discussion

The aim of the present study was twofold. First, we wanted to examine whether the executive functions inhibition, shifting and updating could be distinguished in a non-clinical sample of children aged 9 to 12. The second goal of the study was to examine the relations of these EFs with reading ability, arithmetic ability, and verbal and non-verbal reasoning. Control tasks and CFA were used to separate the effects of executive and non-executive factors.

We first discuss the results pertaining to the first aim. The results of the CFA showed that all control tasks appealed to one underlying ability, which we denoted Naming. Former studies on rapid automatized naming showed that naming speed partly depends on the type of symbols (e.g., van den Bos, Zijlstra, & Lutje Spelberg, 2002; van der Sluis et al., 2004). For example, van den Bos et al. (2002) showed that in participants aged 12 and older, letter and digit naming formed one factor that was distinguishable from a factor for color and picture naming. However, in younger children, an alphanumeric common factor was not identifiable. In the present study, this domain specificity can be recognized in the correlation between the unique variances of letter naming and digit naming. Yet, as a (slightly extended) 1-factor model proved sufficient in this sample, and given the aims of the study (i.e., to study the distinguishableness of EFs after non-executive variance was controlled for), we thought it expedient to treat Naming as a single non-executive control factor.

The Naming factor also explained variance in the manipulated shifting tasks. However, a specific factor for Shifting proved necessary to describe additional relations between the four shifting measures. This indicates that individual differences in the performance of the children on the shifting tasks could not entirely be explained by their performance on the control tasks. Performance on the shifting tasks was thus indicative of more than naming speed alone. Yet, the loadings of the shifting tasks on the Shifting factor were relatively small. In studies were performance on control tasks was not accounted for, the loadings on a shifting factor were mostly .50 or above (Letho et al., 2003; Manly et al., 2001; Miyake et al., 2000). However, the shifting loadings reported by Oberauer et al. (2003), who also accounted for performance on control tasks, are much like the loadings recorded in the current study. So even though a common Shifting factor was still distinguishable after performance on the control tasks was accounted for, the small loadings on this factor imply that only a small portion of the variance in the shifting tasks could actually be attributed to shifting ability. As most variance in these tasks was either non-executive variance or error variance (i.e., not explained by the latent factors), these tasks cannot be considered reliable measures of shifting ability.

In contrast to the Shifting factor, a factor for Inhibition could not be established in the presence of the Naming factor. All variance that the manipulated inhibition tasks had in common could be explained by the Naming control factor. These findings are in line with results reported by Shilling, Chetwynd, and Rabbitt (2002), who found weak and varied correlations (between -.13 and .22) among interference scores of a set of Stroop-like tasks once performance on the control tasks had been taken into account.

The finding that we could not detect an Inhibition factor, even though performance on the inhibition tasks had been markedly slower than on the control tasks, may appear paradoxical. The decelerating effect of the manipulation suggests that the manipulation has broached an additional ability, yet no additional factor was detected. It seems that the inhibition manipulations in this study had not succeeded to generate any discernible differential effects. That is, the extra demands of the inhibition tasks seemed to have had the same effect on all children.

It remains to be established whether other inhibition tasks make for better measures of inhibitory ability. Likely candidates are tasks designed in the Stop paradigm, and the Go/No-go paradigm (see Rubia et al., 2001 for a comparative study). In these tasks, subjects are trained to respond as quickly as possible to certain stimuli, and are then required to withhold from responding, either on cue (Stop task, i.e., inhibition of an already triggered motor response), or according to a rule (Go/No-go task, i.e., rule based response selection). These tasks also provide control conditions. A notable difference with the tasks used in the present study is, that the Stop and Go/No-go tasks require subjects to (unpredictably) refrain from responding altogether, while our Stroop-like tasks required continuous cognitive inhibitory responding, as all trials in the inhibition conditions were incongruent. The continuousness and predictability of the inhibitory requirements may have minimized the need for executive control.

As in other studies, the factor for updating ability proved fairly strong in this study. All updating tasks were substantially related to the updating factor, even though two of the three tasks appeared too easy as many children performed at ceiling level.

The correlation between the factors for Shifting and Updating was very weak in the current study, which means that these EFs should be viewed as separate constructs in children. In previous studies, these correlations were much larger. For instance, Miyake et al. (2000) report a correlation of .56 between Shifting and Updating in an adult population, and Letho et al. (2003) a correlation of .65 in a sample of children. The present lower correlation may partly be due to the presence of the Naming factor, which subsumed some of the non-executive variance shared by the shifting and updating tasks. However, it should be noted that, whereas Letho et al. used a very dissimilar task set, Miyake et al. used indicators for shifting that were quite similar to the present shifting tasks, and which were also corrected for performance on control tasks through the calculation of difference scores. Also, the present updating tasks were adapted from the tasks used by Miyake et al. Whether the dissimilarity of the correlation between Shifting and Updating found in the current study and the study by Miyake et al. is due to differences in the handling of the control tasks (i.e., difference scores vs. regression scores), or genuine differences between adults and children in the factorial structure of executive functioning, merits further research.

The conclusion with regard to the distinguishableness of EFs in children is thus that shifting and updating were detectable as separate EFs in a non-clinical sample of children, while inhibition was not.

The second aim of the study concerned the relations between the EFs on the one hand, and reading ability, arithmetic ability, and verbal and non-verbal reasoning ability on the other. Because all control tasks loaded on one factor, we studied the relation between this non-executive Naming factor and reasoning, arithmetic, and reading as well.

The non-executive Naming factor was strongly related to reading and arithmetic ability. The relation between reading and the ability to rapidly identify and name stimuli has often been reported in reading disabled subgroups (e.g., de Jong & van der Leij, 2003; van den Bos, 1998; van der Sluis et al., 2004; see Share, 1995, and Wolf & Bowers, 1999 for a review), and in non-clinical samples (e.g., de Jong & van der Leij, 2002; de Jong & Wolters, 2002; Manis, Seidenberg, & Doi, 1999; Neuhaus & Swank, 2002; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; van den Bos, Zijlstra, & Lutje Spelberg, 2002). The strength of the present relationship may partly be due to the speeded character of the word reading efficiency task. Yet, relations between naming speed and measures of reading accuracy, reading comprehension, phonological skills, and orthographic skills have also been reported (e.g., de Jong & Wolters, 2002; Manis, Seidenberg, & Doi, 1999; Torgesen et al., 1997). The relations between measures for naming speed and reading can be explained by their mutual requirement to quickly retrieve phonological codes from memory (e.g., Manis et al., 1999; Neuhaus & Swank, 2002; Wolf & Bowers, 1999).

The strong relationship between naming speed and arithmetic ability may seem surprising. The strength of this relation may again partly be due to the speeded character of the arithmetic task. However, links between naming speed and arithmetic ability have also been reported when arithmetic ability was not assessed through a speeded measure (e.g., Bull & Johnston, 1997). At this point, we should emphasize that both measures for reading and arithmetic in this study were efficiency measures. High scores on the reading test were indicative of efficient, fluent, at least partly automatized, reading ability. Likewise, the ability to quickly recognize the visually presented arithmetic problems, or parts thereof, as familiar, and retrieve the accompanying answers from memory, enhances performance on the arithmetic test. So, except for the specific content, these tasks are highly analogous. Interestingly, this communality between the tasks is reflected in the similarity of the amounts of variance that Naming explained in reading (28.1%) and arithmetic (30.3%). This equivalence supports the idea that naming speed is indicative of the accessibility of phonological representations in memory. The equivalence also supports an idea advanced by Geary (1993, 2004) that both reading ability and arithmetic ability depend on the strength and accessibility of representations in memory, and the speed with which this information can be retrieved.

The Naming factor was only slightly related to verbal and non-verbal reasoning. This is comprehensible if naming speed can indeed be interpreted as the speed with which information is retrieved from memory. Reasoning tasks do not measure automatized abilities, and although these tasks often require the retrieval of analogical-relational information, there are no ready answers to the reasoning problems stored in long-term memory. Good performance on reasoning tasks is characterized by careful selection, judgment, and evaluation of all possible relations, rather than quick retrieval of an answer from long-term memory.

In sum, non-executive abilities, as captured by the Naming factor, were substantially related to reading and arithmetic, and only weakly related to verbal and non-verbal reasoning. We now turn to the relationships of the EFs with reading, arithmetic, and verbal non-verbal reasoning.

As was expected based on former studies, updating ability was positively related to reading skill. However, the relation was not very strong, as updating explained only 5% of the variance in reading ability. It is conceivable that the relation would have been stronger if the reading task had required the children to read and comprehend whole sentences, rather than just read unrelated words. Yet, the present finding that updating ability is related to the performance on a measure of automatized reading ability, supports the idea that efficient reading is accompanied by better updating ability.

The relation between updating ability and arithmetic ability was also rather weak, and updating explained only 3% of the variance in arithmetic performance. Like with reading, the weakness of this relation may be due to the nature of the measure used to assess arithmetic ability. Updating has been argued to be involved in the memorization of numbers and subsolutions throughout the arithmetic process (e.g., Geary, 1993, 2004; McLean & Hitch, 1999). However, performance on the arithmetic measure used here profits from arithmetic ability that is at least partly automatized. High scores on such measures indicate high levels of arithmetic fact finding rather than the successful completion of elaborate arithmetical (sub)processes. Updating ability may be more of a requisite for good performance on arithmetic measures that contain more multi-step calculations and word problems (Geary, 2004).

Updating was also related to verbal and especially non-verbal reasoning ability. This relation between updating ability (or working memory capacity) and reasoning ability (IQ) is in line with many previous studies (e.g., Colom et al., 2004; Conway et al, 2002; de Jong & Das-Smaal, 1995; Engle et al, 1999; Kyllonen & Christal, 1990; Oberauer and colleagues, 2000, 2003; Süß et al, 2002). Updating ability is believed to support performance on complex cognitive tasks by enabling subjects to actively revise the content of memory in light of new information. In these verbal and non-verbal analogical reasoning tasks, updating ability is thought to sustain the memorization of all possible analogical relations, and support the process of selection, confirmation, and disposal of possible answers during the comparison process.

The relationships between updating and reasoning that we found in the present study were noticeably weaker than the relations reported by most of the aforementioned authors. Some, as cited by Kyllonen (2002, p.433), argued that the complexity of the tasks used to tap updating capacity (or working memory capacity) accounted for the high correlation with reasoning ability, or g. The updating tasks that we used here were not complex, i.e., did not require the reading of sentences, mental arithmetic, counting, or reasoning (see for instance the updating tasks used by Colom et al., 2004; Conway et al., 2002; Kyllonen & Chrystal, 1990), but only required the recognition of simple stimuli, and the adjustment of the content of memory in light of new information. To the extent that performance was affected by individual differences in symbol identification and naming speed, the Naming factor was used as control. So it is conceivable that the relative ‘purity’ of the present updating tasks may have led to lower correlations with reasoning, as well as with reading, and arithmetic.

However, we should acknowledge that two out of three updating tasks in the present study appeared to be too easy as children performed at ceiling level. This might have resulted in underestimation of the correlations due to restriction of range. The relative easiness of the present updating tasks may therefore also be partly responsible for the low correlations of updating with reasoning ability, and with reading and arithmetic as well.

Shifting ability proved to be related only to non-verbal reasoning, and even this relationship was weak, with shifting only explaining 3% of the variance in non-verbal reasoning. The absence of a correlation between general shifting ability and arithmetic was unexpected. Several authors (e.g., Bull and colleagues, 1999, 2001; McLean & Hitch, 1999; van der Sluis et al., 2004) have reported associations between arithmetic ability and performance on complex shifting tasks like the Wisconsin Card Sorting Task (WCST) and the Making Trails task. Shifting was therefore believed to support alternation between arithmetic strategies (e.g., addition, subtraction, multiplication), and arithmetic sub-solutions in multi-step arithmetic problems. Interestingly enough, the specific relation between arithmetic ability and performance on the Making Trails task was confirmed here. In a study on children with arithmetic disabilities, van der Sluis et al. (2004) found that Trail B was related to arithmetic ability, while another, more simple shifting task (i.e., the same Objects-S tasks as used here) was not. In addition, performance on a task, which required shifting as well as inhibition, was also related to arithmetic ability. Van der Sluis et al. (2004) thereupon suggested that Making Trails tasks appeal to other EFs besides shifting. More specifically, it was hypothesized that Trail B may not only appeal to shifting (i.e., alternation between letters and digits), but to negative priming (i.e., the response, inhibited on trial n-1, is relevant on trial n), and updating (i.e., requirement to keep track of former responses in order to select the correct next response) as well. Notably, the present results support this idea since both Trail A and Trail B appeared to be indicators of updating, besides indicators of shifting. The current finding that *simple* shifting ability is not related to arithmetic ability, while performance on tasks that appeal to different EFs simultaneously is, is therefore in line with the study by van der Sluis et al. (2004). Moreover, the relation of arithmetic ability with the complex Trail B task seems to extend beyond the appeal of Trail B to both shifting and updating. How this additional relation should be explained, is as yet open to question.

The strength of the relationship between shifting ability and arithmetic ability as reported in other studies, may also (partly) have been due to the non-executive requirements of the shifting tasks. If we had not controlled for general naming speed ability in this study, the relationship between shifting performance and arithmetic performance would have turned out to be much stronger.

Yet again, the specific nature of the arithmetic measure may have affected the relation with shifting as well. In the present arithmetic test, shifting between arithmetic strategies from one problem to the next was hardly necessary as the test consisted of three subtests, which were homogeneous with respect to the required arithmetical procedure (i.e., they required either addition, *or* subtraction, *or* multiplication). Shifting may have occurred *within* some of the arithmetic problems - such as shifting from arithmetic fact finding strategies to calculation strategies - but the necessity to shift was clearly minimal. So whether the present lack of correlation between arithmetic and shifting is the result of more pure measurement, or due to the nature of the arithmetic test, is not entirely clear.

The additional specific relationship between the Quantity-I task and arithmetic ability is in concordance with results reported by Bull and Scerif (2001). In 7 to 8 year old children, these authors found that color naming in interference conditions (Stroop) was not related to arithmetic ability, while quantity naming in the interference condition was. The specificity of this relation between arithmetic and Quantity-I is confirmed in the present study, given that arithmetic ability was not related to any of the other putative inhibition measures. Bull and Scerif suggested that the specificity of this relation might indicate domain-specific problem with inhibition, or a domain-specific problem with strategy generation and evaluation (p. 286). We add that the specificity of the relation suggests that arithmetic ability is related to Quantity-I through the non-executive, rather than executive, characteristics of this task.

It is noticeable that the Quantity control task does not seem to share this non-executive characteristic with the Quantity-I task, as the control task is not additionally related with arithmetic ability besides its relation through the Naming control factor. This suggests that pairs of control and manipulated tasks can differ with respect to executive characteristics, as intended, as well as with respect to non-executive characteristics. These latter differences were not expected and require further study.

In sum, the present study demonstrates the usefulness of control tasks in the context of CFA when studying executive functioning. This combination enabled us first, to capture the variance attributable to non-executive task demands, and second, to capture the remaining common variance between the EF tasks, which could then more confidently be attributed to the EFs under study. After controlling for the variance attributable to the non-executive task demands, factors for Shifting and Updating could be distinguished, but not for Inhibition. And, as was to be expected, after accounting for non-executive variance, the correlations between the EFs and reasoning, reading, and arithmetic were lower than reported in earlier studies. Arithmetic and reading ability appeared to be stronger related to the non-executive Naming factor than to shifting and updating. In contrast, for non-verbal reasoning ability a stronger relationship was found with the executive Updating factor than with the non-executive Naming factor.

5

Summary and discussion

The primary objective of the studies reported in this thesis was to investigate how reading and arithmetic ability are related to the functioning of the various components and subroutines of the working memory (WM) system. The WM system is thought to consist of three main components that work together in combining mnemonic functions with regulatory functions. The phonological loop and the visuo-spatial sketchpad effectuate the mnemonic functions, and are responsible for the temporary storage of phonological and visual-spatial information, respectively. The central executive is thought to be responsible for the actuation of the two mnemonic components, and for the regulation of cognitive processing in general. Several regulatory subroutines, also known as executive functions (EFs), have been distinguished within the central executive, including inhibition, shifting, and updating. In this thesis, these components and subroutines were studied in relation to reading and arithmetic, in clinical and non-clinical samples of children.

In this final chapter, the findings of the three studies are summarized. Subsequently, a general conclusion is formulated with regard to the relations between reading, arithmetic, and the WM system. The chapter concludes with a discussion, in which some concerns are addressed regarding the influence of age-related changes on the results of cognitive studies.

Summary

The central question in Chapters 2 and 3 was whether deficits in the mastering of reading and/or arithmetic were related to deficits in (one of) the components, or subroutines of the WM system. The main findings can be summarized as follows.

With regard to mnemonic functioning, the performance of children with specific reading disabilities (RD) and children with specific arithmetic disabilities (AD) was sometimes slightly poorer than that of controls on complex span tasks. However none of these differences were substantial. Children who displayed deficits in both reading and arithmetic (RAD) showed a specific deficit on only one of the complex span tasks, i.e., Digit Span Backward.

In addition, children with AD experienced difficulties with the memorization of dynamic visual information, i.e., information about movement, location, and direction. As children with disabilities in both reading and arithmetic (RAD) did not manifest this problem, this deficit seems specific to children with a simple arithmetic disability.

With regard to executive functioning, children with RD sometimes performed more poorly than controls on executive tasks, but these differences were not attributable to differences in executive functioning. That is, children with RD at times handled the additional non-executive task demands of executive measures less well than controls, but they were not differently affected by the executive task requirements. Children with AD did not experience problems with the individual EFs inhibition and shifting. Their performance on an inhibition task that required the naming of quantities in interference conditions was poorer than the performance of controls. However, this difference was the result of differences in general quantity-naming speed, a non-executive task requirement, rather than of differences in handling inhibitory task demands. Children with AD did however perform more poorly than controls on tasks that required the simultaneous application of different EFs. This difficulty with combining EFs was also present in children with RAD, and can therefore be attributed to the presence of arithmetic disabilities in general.

As an adjunct of the studies on executive functioning, simple naming ability was studied in the differently learning disabled groups, and symbol specific effects were recorded. That is, reading disabilities were associated with slower naming of letters and digits than controls, and arithmetic disabilities were associated with slower naming of digits and quantities than controls.

Finally, an important finding with regard to children with RAD was that all deficits that they displayed in these studies - regarding the components and subroutines of the WM system, and regarding naming speed - could be described as an additive combination of the, sometimes very slight, problems that characterized children with specific learning deficits (i.e., RD or AD). The deficits of children with RAD should therefore not be considered to be different in nature from the problems experienced by children with a simple learning impairment, although their deficits were sometimes more pronounced.

The aim of the study presented in Chapter 4 was first to study the distinguishableness of the proposed executive functions (EFs) inhibition, shifting, and updating in a non-clinical sample of children, and second, to relate the separate EFs to reading and arithmetic ability, and verbal and non-verbal reasoning.

The main findings regarding the structure of executive functioning can be summarized as follows. First, the use of control tasks in the context of confirmatory factor analysis (CFA) enabled us to subsume variance due to non-executive tasks demands (i.e., naming speed requirements) under one factor, and separate it from variance attributable to executive task requirements. In the presence of this strong non-executive Naming factor, factors for the EFs shifting and updating were still distinguishable, while a factor for inhibition was not. Furthermore, the size of the factor loadings, relative to the residual variances, indicated that updating ability could be assessed with reasonable reliability. In contrast, the reliability of the indicators of the indicators of shifting was smaller. The factors for shifting and updating were not substantially correlated, meaning that these EFs could be considered as independent regulatory functions.

Of the three latent factors, the non-executive Naming factor proved by far the most strongly related to arithmetic ability and reading ability. Updating was only weakly related to those scholastic abilities, while the relations with shifting proved to be negligible. Furthermore, updating was moderately related to non-verbal reasoning ability, while naming and shifting were only weakly related to this ability. Both naming and updating were related with verbal reasoning, but again, these relations were weak. In addition to the relations with the factors, arithmetic ability showed a specific relation with a task that required the combination of different EFs simultaneously, and a task that required the naming of quantities in interference conditions. These specific relations were in line with the findings of the study presented in Chapter 3.

Discussion

Below some limitations concerning the current as well as previous studies are discussed. These limitations may have implications for future research.

Symptoms and subtypes

Pennington, van Orden, Kirson, & Haith (1991) summarized six possible relations between a symptom (e.g., WM problems) and a disorder (e.g., dyslexia or dyscalculia). The symptom can be a prerequisite for the disorder (i.e., a primary deficit, underlying the disorder), a facilitator of the disorder, a consequence of the disorder, a correlated symptom, both a prerequisite and a consequence (i.e., reciprocal causation), or an artifactual symptom (i.e., the symptom is artificially related to the disorder). The authors also stated that a symptom can only be a primary symptom if it is universal to the disorder (i.e., all people with the disorder show the symptom), specific to the disorder (i.e., the symptom is exclusive to the disorder), a persistent feature of the disorder, and, most importantly, if the symptom precedes and predicts the disorder.

Following this categorization, the present findings are not consistent with the idea that memory deficits are a primary symptom of reading disabilities. That is, memory deficits may sometimes characterize reading disabled children, as other studies have demonstrated (e.g., de Jong, 1998; Howes, Bigler, Lawson, & Burlingame, 1999; Howes, Bigler, Burlingame, & Lawson, 2003; Siegel & Ryan, 1989; Swanson, 1999; Swanson & Ashbaker, 2000), but these deficits are not universal, or they are not persistent. In Chapter 2, it was hypothesized that dyslexics may show a developmental lag in memory capacity until they learn to read accurately (though slowly), after which memory capacity improves up to age-appropriate levels under the influence of the act of reading itself (see e.g., de Jong & van der Leij, 2003; Van Daal & Van der Leij, 1999, for a similar argumentation). This hypothesis merits further research.

Furthermore, the impaired memory for dynamic visual information of specific arithmetic disabled children has been replicated neither consistently nor frequently. Also, there is at present no evidence that this impairment precedes the arithmetic disability. So for now, the link between specific arithmetic disabilities and visuo-spatial memory remains unclear.

Age, and changing relations

Studying cognitive abilities in children, and evaluating the relations between these abilities is a real challenge. While cognitive abilities may be quite stable during adult life, they certainly are prone to change during the years that children learn, and go to school. Reading and arithmetic ability develop rapidly in young children under the influence of education. These abilities do not only develop with respect to efficiency, but their very nature changes. For instance, fledgling readers do not only read more slowly than experienced readers, they also use different approaches or strategies. Novices mainly using exacting encoding strategies, while advanced readers are, due to practice, better able to use direct word recognition strategies. It is conceivable that consequently (the nature of) relations between scholastic abilities and other cognitive abilities may change, e.g., being substantial at one time, while diminishing thereafter.

These age-related changes in cognitive abilities may be one of the reasons that the many studies on learning disabilities have failed to provide a clear account of causes and correlates. The studies on reading disabilities may serve as an illustrative example. As mentioned earlier, in a good number of studies, children with reading disabilities were found to perform more poorly than controls on tasks appealing to the phonological loop, or to the ability to store and process information simultaneously. However, in some studies, such as the ones presented in Chapter 2, these effects were not replicated. A number of reasons may be offered to account for this inconsistency, such as the use of different selection criteria and measures, and different WM task sets. Yet, it is also possible that the relations between reading ability and WM capacity change with age. For example, working memory capacity may improve up to age-appropriate levels under the influence of development in reading ability itself (as we hypothesized)[10]. In that case, differences in age-ranges between studies (and differences in orthographic consistency) may be the cause of inconsistency in results of these studies.

Because the present studies only focused on an age-restricted subgroup of children, we can only speculate about the nature of these relations. Longitudinal studies are clearly required to shed light on the stability of the relations of reading and arithmetic ability with cognitive abilities such as working memory, and simple access/retrieval processes such as rapid naming ability.

Task impurity, and age related changes

The notion that executive functioning ability develops with age is not disputed. The last decade, some researchers have addressed the development of executive functioning in children, and have tried to expose the developmental trajectories of the different EFs (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Klenberg, Korkman, & Lahti-Nuuttila, 2001; Levin et al., 1991; Welsh, Pennington, & Groisser, 1991). The central aim of these studies was to investigate whether some EFs mature before others.

In the study presented in Chapter 4, it was shown that non-executive task requirements do (sometimes) account for a considerable part of the variability in EF performance. This means that the task impurity problem is real, and this observation may have consequences for developmental studies in the EF field as well.

More specifically, the inevitable impurity of EF tasks entails that distinguishable developmental trajectories of different EFs cannot simply be interpreted in terms of differential maturation of these EFs. Divergent trajectories may also be the result of dissimilar maturation of the other, non-executive cognitive abilities required in the tasks.

---

[10] Note that it is theoretically possible that reading ability improves under the influence of developing working memory capacity. Yet, given the findings of previous studies, this is less likely. The finding that working memory impairments are more frequently reported in dyslexic children who learn to read in deep orthographies, combined with the finding that these dyslexics hardly ever become capable of accurate reading (as dyslexics in shallow orthographies like Dutch do), suggests that the disability to read can harm (working) memory capacity, rather than the other way around.

For example, Klenberg et al. (2001) report that performance on a verbal fluency task, which is sometimes used as a measure of shifting ability, reaches adult levels long after performance on the Statue task, a simple motor inhibition task. The authors conclude that inhibitory ability matures in children before shifting ability does. Yet, such conclusions may not be warranted. After all, performance on the verbal fluency task profits from an extended vocabulary and the development of vocabulary proceeds long into adolescence. In contrast, simple motor skills, such as required in the Statue task, reach developmental asymptotes much earlier. The task impurity problem thus not only constitutes a considerable threat to the interpretation of research results in differential studies, but also in developmental studies.

Developing abilities, and wide age-ranges

The suggestion that EFs mature with age, and that different EFs develop along different timelines, implies that the same EF tasks may appeal to different abilities in different age groups. It also implies that the factorial structure of executive functioning may change over time (e.g., Anderson et al, 2001). It is therefore not recommended to perform factor analysis on samples with wide age-range, as the resulting factorial structures may not be interpretable or representative for any of the age groups (Meredith, 1993). Also, the possibility exists that the resulting factorial structure is mostly indicative of age-related variability in performance, rather than variability in executive capacity.

In some recent studies that have addressed the structure of executive functioning in children, either through exploratory or confirmatory factor analysis, (i.e., Anderson et al., 2001; Klenberg et al., 2001; Letho, Juujärvi, Kooistra, & Pulkkinen, 2003; Levin et al., 1991; Manly et al., 2001; Welsh et al., 1991), the age spans of the participating samples were considerable. Manly et al. and Klenberg et al. based their factor analyses on samples ranging in age between 6 and 12, and 3 and 12, respectively. The age ranges in the studies of Anderson et al., Levin et al., and Letho et al. were 11-17, 7-15, and 8-13, respectively, and Welsh et al. pooled the data of an 8-12 year old subgroup with the data of adult subjects for their factor analysis.

Whether these age-ranges are acceptable, or what ranges are, depends entirely on the developmental timelines of the different EFs. Yet, as long as these are themselves the subject of study, it seems prudent to use samples with relatively small age-ranges. Whether the age-range of the sample in our structural study (age ranging between 9 and 12) was ‘restricted enough’ is as yet hard to determine. It was however small in comparison to the ranges observed in the previous studies mentioned above.

Conclusion

The central aim of all three empirical studies in this thesis was to investigate the relationships between reading and arithmetic ability on the one hand, and the WM system, with all its components and subroutines, on the other. Different experimental designs, and different statistical analyses were used to unravel these relations, and to address the accompanying measurement problems.

In conclusion, the three studies have yielded little evidence that reading ability is related to the functioning of the components or subroutines of the WM system. Arithmetic ability, however, was positively and substantially related to the ability to combine different regulatory functions simultaneously. Furthermore, children with a specific arithmetic impairment showed a deficit with regard to the dynamic/spatial part of the visuo-spatial sketchpad. The problems that children with deficits in both reading and arithmetic experienced proved a combination of the (at times slight) deficits displayed by children with simple learning deficits. Finally, naming speed, or the ability to rapidly identify and name symbols, proved to be related to reading and arithmetic ability in non-clinical children, and symbol-specific impairments were observed in children with learning disabilities. Following Geary (1993, 2004), this key role of rapid naming ability is supports the idea that both reading ability and arithmetic ability depend on the strength, quality, and accessibility of representations in memory.

With regard to the executive subroutines, the studies presented in Chapter 3 and 4 have clearly shown that executive functioning is difficult to assess properly, because non-executive task requirements can obfuscate conclusions about the distinctness of the separate executive functions, about assets and deficits in executive functioning (especially in clinical populations), and about the relations between separate executive functions and other cognitive abilities such as reading and arithmetic. Additional studies on the validity of executive measures are required to disentangle the processes that underlie development in executive functioning, and to shed light on the nature of the relations between performance on executive tasks and other cognitive abilities.

References

Aarnoutse, C., Leeuwe, J. v., & Verhoeven, L. (2000). Ontwikkeling van beginnende geletterdheid. *Pedagogische Studiën, 77*, 307-325.

Adams, J. W., & Hitch, G. J. (1997). Working memory and children's mental addition. *Journal of Experimental Child Psychology, 67*, 21-38.

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of executive functions through late childhood and adolescence in an Australian sample. *Developmental Neuropsychology, 20*(1), 385-406.

Baddeley, A. D., & Hitch, G. J. (1974). Working Memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-90). New York: Academic Press.

Baddeley, A. D. (1996). Exploring the Central Executive. *The Quarterly Journal of Experimental Psychology, 49A*(1), 5-28.

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*(1), 158-173.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: the multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: mechanisms of active maintenance and executive control* (pp. 28-61). Cambridge: Cambridge University Press.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65-94.

Bast, J. W., & Reitsma, P. (1998). Analyzing the development of individual differences in terms of Matthew effects in reading: results from a Dutch longitudinal study. *Developmental psychology, 34*(6), 1373-1399.

Bedard, A.-C., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Developmental Neuropsychology, 21*(1), 93-111.

Bentler, P. M. (1990). Comparative fit indexes in structural models. Psychological Bulletin, 107, 238-246.

Bleichrodt, N., Drenth, P. J. D., Zaal, J. N., & Resing, W. C. M. (1987). *RAKIT; Revisie Amsterdamse Kinder Intelligentie Test.* Lisse: Swets & Zeitlinger Publishers.

Bollen, K., & Long, J. S. (Eds.). (1993). Testing structural equation models. Newbury Park, CA: Sage.

Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds.), Testing structural equation models (pp. 136-162). Newbury Park, CA: Sage.

Brus, B. T., & Voeten, M. J. M. (1995). *Een Minuut Test.* Lisse: Swets & Zeitlinger Publishers.

Bull, R., & Johnston, R. S. (1997). Children's arithmetic difficulties: contributions from processing speed, item identification, and short-term memory. *Journal of Experimental Child Psychology, 65*, 1-24.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15*(3), 421-442.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching and working memory. *Developmental Neuropsychology, 19*(3), 273-293.

Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81-116). Hove, UK: Psychology Press

Butterworth, B. (1999) The Mathematical Brain. London: Macmillan.

Campbell, D.T., & Fiske, D.W. (1959). Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological Bulletin, 56*, 81-104.

Cantor, J., Engle, R. W., & Hamilton, G. (1991). Short-Term Memory, Working Memory, and Verbal Abilities: How Do The Relate? *Intelligence, 15*, 229-246.

Carter, C. S., Krener, P., Chaderjian, M., Northcutt, C., & Wolfe, V. (1995). Abnormal processing of irrelevant information in attention deficit hyperactivity disorder. *Psychiatry Research, 56*, 59-70.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33*, 386-404.

Christ, S. E., White, D. A., Mandernach, T., & Keys, B. A. (2001). Inhibitory control across the life span. *Developmental Neuropsychology, 20*(3), 653-669.

Colom, R., Rebollo, I., Palacios, A., Juan-Espinosa, M., & Kyllonen, P. C. (2004). Working memory is (almost) perfectly predicted by *g*. *Intelligence, 32*, 277-296.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Monkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence, 30*, 163-183.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450-466.

Daneman, M. (1987). Reading and working memory. In J. R. Beech & A. M. Colley (Eds.), *Cognitive approaches to reading* (pp. 57-86): John Wiley & Sons Ltd.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: a meta-analysis. *Psychonomic Bulletin & Review, 3*(4), 422-433.

De Bruyn, E. E. J., Van der Steene, G., Van Haasen, P. P., Coetsier, P., Pijl, Y. J., Spoelders-Claes, R., et al. (1986). *Wechsler Intelligence Scale for Children - Revised (WISC-R)*. Lisse: Swets & Zeitlinger Publishers.

De Jong, P. F., & Das-Smaal, E. A. (1995). Attention and intelligence: the validity of the Star Counting test. *Journal of Educational Psychology, 87*(1), 80-92.

De Jong, P. F. (1998). Working memory deficits of reading disabled children. *Journal of Experimental Child Psychology, 70*, 75-96.

De Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: results from a Dutch latent variable longitudinal study. Journal of Educational Psychology, 91(3), 450-476.

De Jong, P. F., & Van der Leij, A. (2002). Effects of phonological abilities and linguistic comprehension on the development of reading. *Scientific studies of reading, 6*, 51-77.

De Jong, P. F., & van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *Journal of Educational Psychology, 95*(1), 22-49.

De Jong, P. F., & Wolters, G. (2002). Fonemisch bewustzijn, benoemsnelheid en leren lezen. *Pedagogische Studiën, 79*, 53-63.

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (1999). The contribution of working memory resources in the verification of simple mental arithmetic sums. *Psychological Research, 62*, 72-77.

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and the central executive involved? *Memory & Cognition, 29*(2), 267-273.

De Vos, T. (1992). *Tempo Test Rekenen.* Lisse: Swets & Zeitlinger Publishers.

Deary, I. J. (2002). *g* and cognitive elements of information processing: an agnostic view. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence - How general is it?* (pp. 151-181). London: Lawrence Erlbaum Associates, Publishers.

Denckla, M. B. (1994). Measurement of executive function. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities: new views on measurement issues* (pp. 117-142). Baltimore: P.H.Brookes Publishing.

Denckla, M. B. (1996). A theory and model of executive function: A neuropsychological perspective. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 263–277). Baltimore: MD: Paul H. Brookes.

Denckla, M. B., & Rudel, R. G. (1976). Rapid automatized naming (RAN): Dyslexic differentiated from other learning disabilities. *Neuropsychologia*, 14, 471-479.

Engle, R. W., Laughlin, J. E., Tuholski, S. W., & Conway, A. R. A. (1999). Working memory, short term memory en general fluid intelligence: a latent variable approach. *Journal of Experimental Psychology: General, 128*(3), 309-331.

Everatt, J., Warner, J., Miles, T. R., & Thomson, M. E. (1997). The incidence of Stroop interference in dyslexia. *Dyslexia, 3*, 222-228.

Fischer, M. H. (2001). Probing spatial working memory with the corsi blocks task. *Brain and Cognition, 45*, 143-154.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *Journal of Experimental Psychology: General, 133*(1), 101-135.

Fürst, A. J., & Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmic. *Memory & Cognition, 28*(5), 774-782.

Gathercole, S. E., & Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology, 70*, 177-194.

Geary, D. C., Brown, S. C., & Samanayake, V. A. (1991). Cognitive addition: strategy choice and speed-of-processing differences in gifted, normal, and mathematically disabled children. *Developmental Psychology, 27*(3), 398-406.

Geary, D. C. (1993). Mathematical disabilities: cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114*(2), 345-362.

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology, 74*, 213-239.

Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arthmetical cognition: a longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology, 77*, 236-263.

Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37*(1), 4-15.

Graf, P., & Uttl, B. (1995). Color- and picture-word Stroop tests: performance changes in old age. *Journal of Clinical and Experimental Neuropsychology, 17*, 1-16.

Gustafsson, J. E. (1992). The relevance of factor analysis for the study of group differences. *Multivariate Behavioral Research, 27*(2), 239-247.

Gustafsson, J. E., & Undheim, J. O. (1992). Stability and change in broad and narrow factors of intelligence from ages 12 to 15 years. *Journal of Educational Psychology, 84*(2), 141-149.

Hecht, S. A. (2002). Counting on working memory in simple arithmetic when counting is used for problem solving. *Memory & Cognition, 30*(3), 447-455.

Helland, T., & Asbjørnsen, A. (2000). Executive functions in dyslexia. *Child Neuropsychology, 6*(1), 37-48.

Henry, L. A. (2001). How does the severity of a learning disability affect working memory performance? *Memory, 9*(4/5/6), 233-247.

Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetic learning difficulties. *British Journal of Psychology, 82*, 375-386.

Holopainen, L., Ahonen, T., & Lyytinen, H. (2001). Predicting delay in reading achievement in a highly transparent language. *Journal of Learning Disabilities, 34*(5), 401-413.

Howes, N. L., Bigler, E. D., Lawson, J. S., & Burlingame, G. M. (1999). Reading disability subtypes and the test of memory and learning. *Archives of Clinical Neuropsychology, 14*(3), 317-339.

Howes, N. L., Bigler, E. D., Burlingame, G. M., & Lawson, J. S. (2003). Memory performance of children with dyslexia: a comparative analysis of theoretical perspectives. *Journal of Learning Disabilities, 36*(3), 230-246.

Jacques, S., & Zelazo, P. D. (2001). The Flexible Item Selection Task (FIST): a measure of executive function in preschoolers. *Developmental Neuropsychology, 20*(3), 573-591.

Jöreskog, K. G. (1993). Testing structural equation models. In K. A. Bollen & J. S. Long (Eds.), *Testing structural equation models* (pp. 294-316). Newbury Park, CA: Sage.

Jöreskog, K. G., & Sörbom, D. (2001). *LISREL 8.50: User's reference guide.* Chicago: Scientific Software International.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132*(1), 47-70.

Klenberg, L., Korkman, M., & Lahti-Nuuttila, P. (2001). Differential development of attention and executive functions in 3- to 12-year-old Finnish children. *Developmental Neuropsychology, 20*(1), 407-428.

Klorman, R., Hazel-Fernandez, L. A., Shaywitz, S. E., Fletcher, J. M., Marchione, K. E., Holahan, J. M., et al. (1999). Executive functioning deficits in attention-deficit / hyperactivity disorder are independent of oppositional defiant or reading disorder. *Journal of the American Academy of Child and Adolescent Psychiatry, 38*(9), 1148-1155.

Kyllonen, P. C. (1993). Aptitude testing inspired by information processing: A test of the four-sources model. *The Journal of General Psychology, 120(3)*, 375-405.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity ?! *Intelligence, 14*, 389-433.

Kyllonen, P. C. (2002). g: knowledge, speeds, strategies, or working-memory capacity? A systems perspective. In R. J. Sternberg & E. L. Grigorenko (Eds.), *The general factor of intelligence - How general is it?* (pp. 415-445). London: Lawrence Erlbaum Associates, Publishers.

Lemaire, P., Abdi, H., & Fayol, M. (1996). The role of working memory resources in simple cognitive arithmetic. *European Journal of Cognitive Psychology, 8*(1), 73-103.

Letho, J. E., Juujärvi, Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: evidence from children. *British Journal of Development Psychology, 21*, 59-80.

Levin, H. S., Culhane, K. A., Hartmann, J., Evankovich, K., Mattson, A. J., Harward, H., et al. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology, 7*(3), 377-395.

Levine, J. H. (1993). *Exceptions are the rule: an inquiry into methods in the social sciences*: Westview Press.

Lindsay, R. L., Tomazic, T., Levine, M. D., & Accardo, P. J. (1999). Impact of attentional dysfunction in dyscalculia. *Developmental Medicine & Child Neurology, 41*, 639-642.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory & Cognition, 22*(4), 395-410.

Lyytinen, H., Ahonen, T., Eklund, K., Guttorm, T. K., Laakso, M. L., Leinonen, S., et al. (2001). Developmental pathways of children with and without familial risk for dyslexia during the first years of life. *Developmental Neuropsychology, 20*(2), 535-554.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: in integrative review. *Psychological Bulletin, 109*(2), 163-203.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading, 3*(2), 129-157.

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., & Robertson, I. H. (2001). The differential assessment of children's attention: the Test of Everyday Attention for Children (TEA-Ch), normative sample data and ADHD performance. *Journal of Child Psychology and Psychiatry, 42*(8), 1065-1081.

Marsh, H. W. (1989). Confirmatory factor analysis of multitrait-multimethod data: many problems and a few solutions. *Applied Psychological Measurement, 13*(4), 335-361.

Marsh, H. W., & Bailey, M. (1991). Confirmatory factor analyses of multitrait-multimethod data: a comparison of alternative models. *Applied Psychological Measurement, 15*(1), 47-70.

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia. *Cognition, 44*, 107-157.

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning disabilities. *Journal of Experimental Child Psychology, 74*, 240-260.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. Cognitive Psychology, 41, 49-100.

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: the role of the central executive. *British Journal of Psychology, 81*, 111-121.

Neuhaus, G., Foorman, B. R., Francis, D. J., & Carlson, C. D. (2001). Measures of information processing in rapid automatized naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology, 78*, 359-373.

Neuhaus, G. F., & Swank, P. R. (2002). Understanding the relations between RAN letter subtest components and word reading in first-grade students. *Journal of Learning Disabilities, 35*(2), 158-174.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin, 126*(2), 220-246.

Noël, M. P., Désert, M., Aubrun, A., & Seron, X. (2001). Involvement of Short-Term Memory in Complex Mental Calculation. *Memory & Cognition, 29*(1), 34-42.

Nopola-Hemmi, J., Myllyluoma, B., Voutilainen, A., Leinonen, S., Kere, J., & Ahonen, T. (2002). Familial dyslexia: neuro-cognitive and genetic correlation in a large Finnish family. *Developmental Medicine & Child Neurology, 44*, 580-586.

Oberauer, K., Süß, H.-M., Schulze, R., Wilhelm, O., & Wittman, W. W. (2000). Working memory capacity - facets of a cognitive ability construct. *Personality and Individual Differences, 29*, 1017-1045.

Oberauer, K., Süß, H.-M., Wilhelm, O., & Wittman, W. W. (2003). The multiple faces of working memory: storage, processing, supervision, and coordination. *Intelligence, 31*, 167-193.

Pennington, B. F., Van Orden, G., Kirson, D., & Haith, M. (1991). What is the causal relation between verbal STM problems and dyslexia? In S. A. Brady & D. P. Shankweiler (Eds.), *Phonological processes in literacy* (pp. 173-186). Hillsdale NJ: Lawrence Erlbaum Associates.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry, 37*, 51-87.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage, 15*, 435-446.

Pickering, S. J., Gathercole, S. E., Hall, M., & Lloyd, S. A. (2001). Development for memory for pattern and path: Further evidence for the fractionation of visuo-spatial memory. *The Quarterly Journal of Experimental Psychology, 54a*, 000-000.

Pickering, S. J. (2001). Cognitive approaches to the fractionation of visuo-spatial working memory. *Cortex, 37*, 457-473.

Porpodas, C. D. (1999). Patterns of phonological and memory processing in beginning readers and spellers in Greek. *Journal of Learning Disabilities, 32*(5), 406-416.

Rabbitt, P. (1997). Introduction: Methodologies and models in the study of executive function. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 1-38). Hove, UK: Psychology Press.

Raven, J. C., Court, J. H., & Raven, J. (1979). *Manual for Raven's progressive matrices and vocabulary scales. Section I General overview*. London: H.K. Lewis & Co.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*(2), 207-231.

Rourke, B. P. (1993). Arithmetic disabilities, specific and otherwise: a neuropsychological perspective. *Journal of Learning Disabilities, 26*(4), 214-226.

Rourke, B. P., & Del Dotto, J. E. (1994). *Learning Disabilities - A neuropsychological Perspective*: Sage Publications, Inc.

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., et al. (2001). Mapping motor inhibition: conjunctive brain activations across different versions of Go/No-Go and Stop tasks. *NeuroImage, 13*, 250-261.

Scheres, A., Oosterlaan, J., Geurts, H., Morein-Zamir, S., Meiran, N., Schut, H., et al. (2004). Executive functioning in boys with ADHD: Primarily an inhibition deficit? *Archives of Clinical Neuropsychology, 19*, 569-594.

Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). Evaluating the fit of structural equation models: test of significance and descriptive goodness-of-fit measures. *Methods of Psychological Research, 8*(2), 23-74.

Seidman, L. J., Biederman, J., Monuteaux, M. C., Weber, W., & Faraone, S. V. (2000). Neuropsychological functioning in nonreferred siblings of children with attention deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 109*(2), 252-265.

Sergeant, J. A., Geurts, H., & Oosterlaan, J. (2002). How specific is a deficit of executive functioning for attention-deficit/hyperactivity disorder? *Behavioral Brain Research, 130*, 3-28.

Seymour, P. H. K., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94*, 143-174.

Shallice, T., Marzocchi, G. M., Coser, S., Del Savio, M., Meuter, R. F., & Rumiati, R. I. (2002). Executive function profile in children with attention deficit hyperactivity disorder. *Developmental Neuropsychology, 21*(1), 43-71.

Share, D. L., Moffitt, T. E., & Silva, P. A. (1988). Factors associated with arithmetic-and-reading disability and specific arithmetic disability. *Journal of Learning Disabilities, 21*(5), 313-320.

Share, D. L. (1995). Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition, 55*, 151-218.

Shilling, V. M., Chetwynd, A., & Rabbitt, P. M. A. (2002). Individual inconsistency across measures of inhibition: an investigation in the construct validity of inhibition in older adults. *Neuropsychologia, 40*, 605-619.

Siegel, L. S., & Ryan, E. B. (1988). Development of grammatical-sensitivity, phonological, and short-term memory skills in normally achieving and learning disabled children. *Developmental Psychology, 24*(1), 28-37.

Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development, 60*, 973-980.

Sikora, D. M., Haley, P., Edwards, J., & Butler, R. W. (2002). Tower of London test performance in children with poor arithmetic skills. *Developmental Neuropsychology, 21*(3), 243-254.

Sonuga-Barke, E. J. S., Dalen, L., Daley, D., & Remington, B. (2002). Are planning, working memory, and inhibition associated with individual differences in preschool ADHD symptoms? *Developmental Neuropsychology, 21*(3), 255-272.

Starkey, P., & Cooper, R. G. J. (1995). The development of subitizing in young children. *British Journal of Developmental Psychology, 13*, 399-420.

Stephan, K.E., Marshall, J.C., Friston, K.J., Rowe, J.B., Ritzl, A, Zilles, K., & Fink, G.R. (2003). Lateralized cognitive processes and lateralized task control in the human brain. *Science, 301*, 384-386.

Stevens, J., Quittner, A. L., Zuckerman, J. B., & Moore, S. (2002). Behavioral inhibition of self-regulation of motivation and working memory in children with Attention Deficit Hyperactivity Disorder. *Developmental Neuropsychology, 21*, 117-140.

Strang, J. D., & Rourke, B. P. (1983). Concept-formation/non-verbal reasoning abilities in children who experience specific academic problems with arithmetic. *Journal of Clinical Child Psychology, 12*(1), 33-39.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-662.

Süß, H.-M., Oberauer, K., Wittman, W. W., Wilhelm, O., & Schulze, R. (2002). Working-memory capacity explains reasoning ability - and a little bit more. *Intelligence, 30*, 261-288.

Svenson, O., & Sjöberg, K. (1983). Speeds of subitizing and counting processes in different age groups. *The Journal of Genetic Psychology, 142*, 203-211.

Swanson, H. L. (1993). Individual differences in working memory: a model testing and subgroup analysis of learning disabled and skilled readers. *Intelligence, 17*, 285-332.

Swanson, H. L. (1994). The role of working memory and dynamis assessment in the classification of children with learning disabilities. *Learning Disabilities Research, 9*(4), 190-202.

Swanson, H. L. (1999). Reading comprehension and working memory in learning disabled readers: is the phonological loop more important tahn the executive system? *Journal of Experimental Child Psychology, 72*, 1-31.

Swanson, H. L., & Ashbaker, M. H. (2000). Working memory, short-term memory, speech rate, word recognition and reading comprehension in learning disabled readers: does the executive system have a role? *Intelligence, 28*(1), 1-30.

Swanson, H. L., & Sachse-Lee, C. (2001). A subgroup analysis of working memory in children with reading disabilities: domain-general or domain-specific deficiency? *Journal of Learning Disabilities, 34*(3), 249-263.

Swanson, H. L., & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: both executive and phonological processes are important. *Journal of Experimental Child Psychology, 79*, 294-321.

Swanson, H. L. (2003). Age-related differences in learning disabled and skilled reader's working memory. *Journal of Experimental Child Psychology, 85*, 1-31.

Taylor, H. G., Albo, V. C., Phebus, C., Sachs, B. R., & Bierl, P. G. (1987). Post irradiation treatment outcomes for children with acute lymphocytic leukemia. *Journal of Pediatric Psychology, 12*, 394-411.

Taylor, H. G., Mills, H. L., Ciampi, A., du Berger, R., Watters, G. V., Gold, R., et al. (1990). The sequelae of Haemophilus influenzae meningitis in school-age children. *The New England Journal of Medicine, 323*(24), 1657-1663.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatized naming ability to the growth of word-reading skills in second- to fifth-grade children. *Scientific Studies of Reading, 1*(2), 161-185.

Uttl, B., & Graf, P. (1997). Color-word Stroop test performance across the adult life span. *Journal of Clinical and Experimental Neuropsychology, 19*, 405-420.

Van Daal, V., & van der Leij, A. (1999). Developmental dyslexia: related to specific or general deficits? *Annals of Dyslexia, 49*, 71-104.

Van den Bos, K. P. (1998). IQ, phonological awareness and continuous-naming speed related to Dutch poor decoding children's performance on two word identification tests. *Dyslexia, 4*, 73-89.

Van den Bos, K. P., Zijlstra, B. H. J., & Lutje Spelberg, H. C. (2002). Life-span data on continuous-naming speeds of numbers, letters, colors, and pictured objects, and word-reading speed. *Scientific Studies of Reading, 6*(1), 25-49.

Van der Schoot, M., Licht, R., Horsley, T. M., & Sergeant, J. A. (2000). Inhibitory deficits in reading disability depend on subtype: guessers but not spellers. *Child Neuropsychology, 6*(4), 297-312.

Van der Schoot, M., Licht, R., Horsley, T. M., & Sergeant, J. A. (2002). Fronto-central dysfunctions in reading disability depend on subtype: guessers but not spellers. *Developmental Neuropsychology, 22*(3), 533-564.

Van der Sluis, S., de Jong, P. F., & van der Leij, A. (2004). Inhibition and shifting in children with learning deficits in arithmetic and reading. *Journal of Experimental Child Psychology, 87*, 239-266.

Van der Sluis, S., van der Leij, A., & de Jong, P. F. (in press). Working memory in Dutch children with reading and arithmetic related learning deficits. *Journal of Learning Disabilities.*

Welsh, M. C., Pennington, B. F., & Groisser, D. B. (1991). A normative-developmental study of executive function: a window on prefrontal function in children. *Developmental Neuropsychology, 7*(2), 131-149.

Wesseling, R., & Reitsma, P. (2000). The transient role of explicit phonological recoding for reading acquisition. *Reading and Writing: An Interdisciplinary Journal, 13*, 313-336.

West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging, 13*(2), 206-217.

Weyandt, L. L., Rice, J. A., Linterman, I., Mitzlaff, L., & Emert, E. (1998). Neuropsychological performance of a sample of adults with ADHD, developmental reading disorder, and controls. *Developmental Neuropsychology, 14*, 643-656.

Willcutt, E. G., Pennington, B. F., Boada, R., Ogline, J. S., Tunick, R. A., Chhabildas, N. A., et al. (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 110*(1), 157-172.

Wilson, K. M., & Swanson, H. L. (2001). Are mathematics disabilities due to a domain-general or a domain-specific working memory deficit? *Journal of Learning Disabilities, 34*(3), 237-248.

Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics, 14*, 1-33.

Wimmer, H., Mayringer, H., & Landerl, K. (1998). Poor reading: a deficit in skill-automatization or a phonological deficit? *Scientific Studies of Reading, 2*(4), 321-340.

Wimmer, H., Mayringer, H., & Landerl, K. (2000). The double-deficit hypothesis and difficulties in learning to read a regular orthography. *Journal of Educational Psychology, 92*(4), 668-680.

Wimmer, H., & Mayringer, H. (2002). Dysfluent reading in the absence of spelling difficulties: a specific disability in regular orthographies. *Journal of Educational Psychology, 94*(2), 272-277.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*(3), 415-438.

Wu, K. K., Anderson, V., & Castiello, U. (2002). Neuropsychological evaluation of deficits in executive functioning for ADHD children with and without additional learning disabilities. *Developmental Neuropsychology, 22*(2), 501-531.

Yap, R., & van der Leij, A. (1993). Word processing in dyslexics: An automatic decoding deficit? *Reading and Writing, 5,* 261-279.

Yntema, D.B. (1963). Keeping track of several things at once. *Human Factors, 5*, 7-17.

Zar, J. H. (1999). *Biostatistical analysis* (4th ed.). London: Prentice Hall.

Nederlandse samenvatting

In de drie empirische studies die in dit proefschrift zijn gebundeld, werden de relaties onderzocht tussen de werkgeheugencapaciteit, en de lees- en rekenvaardigheid van kinderen. Het werkgeheugen is een complex systeem waarin geheugenprocessen gecombineerd worden met zogenaamde executieve, ofwel regulerende, functies. In de twee geheugenmodules, de fonologische lus (phonological loop) en het visueel-spatiële kladblok (visuo-spatial sketchpad), kan informatie van respectievelijk fonologische en visueel-spatiële aard kortstondig worden opgeslagen. Deze twee modules worden aangestuurd door een derde component, de centrale executieve (central executive), die daarnaast ook een algemeen superviserende rol heeft. Middels de executieve functies is de centrale executieve verantwoordelijk voor het reguleren, organiseren, controleren en coördineren van cognitieve activiteit in het algemeen. In dit proefschrift ligt de nadruk op drie van deze executieve functies, namelijk inhibitie, shifting (flexibiliteit), en updating. Inhibitie is de vaardigheid om dominante of automatische responsen te onderdrukken ten gunste van responsen die meer gepast zijn. De vaardigheid om snel tussen strategieën of taken te wisselen, wordt shifting genoemd. Updating betreft de vaardigheid om de inhoud van het geheugen aan te passen aan nieuwe informatie, en up-to-date te houden.

In hoofdstuk 2 werden de geheugenfuncties van het werkgeheugensysteem onderzocht met betrekking tot leerproblemen. Onderzoek naar de geheugenfuncties van het werkgeheugensysteem richt zich op de twee geheugenmodules en de aan het geheugen gelieerde executieve functie updating, gemeten middels zogenaamde complexe spantaken. Uit verschillende voorgaande onderzoeken was gebleken dat kinderen met leerproblemen op het gebied van lezen en/of rekenen minder (werk-) geheugencapaciteit hebben dan kinderen zonder leerproblemen. In deze onderzoeken stond echter vaak maar één type leerstoornis centraal. De studies in hoofdstuk 2 vormen een aanvulling op eerder onderzoek. In deze studies werd de (werk-) geheugencapaciteit van kinderen met enkelvoudige leesproblemen, kinderen met enkelvoudige rekenproblemen, en kinderen met zowel lees- als rekenproblemen, vergeleken met de (werk-) geheugencapaciteit van kinderen zonder leerproblemen (zogenaamde controle kinderen). Door kinderen met verschillende typen leerstoornissen tegelijkertijd te onderzoeken, was directe vergelijking tussen groepen mogelijk. De vragen die centraal stonden in hoofdstuk 2 waren a) of leerstoornissen op het gebied van lezen en/of rekenen gerelateerd zijn aan deficiënties in een of meer van de geheugencomponenten van het werkgeheugensysteem, en b) of groepen met verschillende leerstoornissen ook verschillende geheugendeficiënties vertonen.

Uit dit onderzoek bleek dat leerstoornissen niet gerelateerd waren aan deficiënties in de capaciteit van de fonologische lus: kinderen met leerproblemen scoorden evengoed op fonologische lus-taken als kinderen zonder leerproblemen. Kinderen met leesproblemen, en kinderen met lees- en rekenproblemen, scoorden ook even goed als controle kinderen op visueel-spatiële geheugentaken. Kinderen met enkelvoudige rekenproblemen bleken geen moeite te hebben met het onthouden van statische visuele informatie, ofwel informatie over vorm en locatie. Wel hadden deze kinderen meer moeite met het onthouden van dynamische visuele informatie, ofwel informatie over beweging en richting. Omdat kinderen met lees- en rekenstoornissen dit probleem met het onthouden van dynamisch visuele informatie niet deelden, lijkt dit probleem specifiek voor kinderen met een enkelvoudige rekenstoornis, en niet toe te schrijven aan de aanwezigheid van rekenproblemen in het algemeen.

Verder bleek dat kinderen met enkelvoudige leerstoornissen in rekenen en lezen iets minder goed scoorden op complexe spantaken dan controle kinderen, maar deze verschillen waren niet substantieel. Kinderen met meervoudige leerstoornissen scoorden minder goed dan controle kinderen op één specifieke complexe spantaak, namelijk de Digit Span Backward. Dit specifieke probleem van kinderen met lees- en rekenproblemen bleek het best beschreven te kunnen worden als een optelling van de kleine problemen die de kinderen met enkelvoudige leerstoornissen in rekenen en lezen hadden met deze taak. Dit probleem van kinderen met lees- en rekenproblemen is dus niet anders van aard dan de problemen van kinderen met een enkelvoudige stoornis, maar wel meer uitgesproken. Omdat problemen met complexe spantaken alleen tot uiting kwamen op de Digit Span Backward, en niet op de andere complexe span taken, kan niet geconcludeerd worden dat werkgeheugen in het algemeen een probleem vormt voor kinderen met leerstoornissen. De vraag blijft dan ook welke specifieke kenmerken van de Digit Span Backward taak de bron van de moeilijkheden vormden.

In hoofdstuk 3 wordt een studie gerapporteerd waarin opnieuw kinderen met verschillende typen leerstoornissen werden onderzocht, maar nu met betrekking tot de executieve functies inhibitie en shifting. De vragen die centraal stonden waren a) of leerstoornissen op het gebied van lezen en/of rekenen gerelateerd zijn aan problemen met inhibitie en/of shifting, en b) of de groepen met verschillende leerstoornissen verschillende deficiënties vertoonden.

Een probleem bij het meten van executieve functies is dat deze functies niet direct gemeten kunnen worden, maar een taakcontext nodig hebben om zich te kunnen manifesteren. Executieve taken doen dus ook altijd een beroep op andere, non-executieve vaardigheden zoals verbaal vermogen, reactiesnelheid, benoemsnelheid, of visueel vermogen. Verschillen tussen groepen in scores op executieve taken kunnen dus niet zonder meer toegeschreven worden aan verschillen in executief functioneren, maar kunnen ook voortkomen uit verschillen met betrekking tot de non-executieve taakeisen. Om executieve functies toch nauwkeurig te kunnen meten, werd in deze studie gebruik gemaakt van controle taken. Het idee van controle taken is dat deze alleen van de executieve taken verschillen met betrekking tot de executieve, maar niet met betrekking tot de non-executieve taakeisen. De meeste controletaken in deze studie bestonden uit benoemtaken, ofwel taken waarbij kinderen zo snel mogelijk stimuli (letters, cijfers, objecten, of hoeveelheden) moeten benoemen. Deze taken werden vervolgens gemanipuleerd zodat ze ook beroep deden op inhibitie en shifting.

Uit aparte analyses voor de controle benoemtaken kwamen symboolspecifieke defecten naar voren. Leesproblemen bleken samen te gaan met het langzamer benoemen van letters en cijfers, terwijl rekenproblemen samengingen met het langzamer benoemen van cijfers en hoeveelheden. De benoemproblemen waren het sterkst aanwezig in de groep van kinderen met lees- en rekenproblemen. Opnieuw bleek dat de problemen van deze groep beschreven konden worden als een additionele combinatie van de minder prominente benoemproblemen die kinderen met een enkelvoudige leerstoornis ondervonden. De problemen van kinderen met een meervoudige leerstoornis waren dus wel groter, maar niet van een andere aard.

Met betrekking tot de executieve taken bleek dat kinderen met enkelvoudige leesproblemen soms minder goed scoorden dan controle kinderen, maar deze verschillen konden worden toegeschreven aan de verschillen die al bestonden op de controle taken, ofwel, aan verschillen in non-executieve (benoem-) vaardigheden. Kinderen met enkelvoudige leesproblemen hadden dus niet meer moeite met inhibitie, shifting, of het combineren van inhibitie en shifting, dan kinderen zonder leerproblemen. Kinderen met enkelvoudige rekenproblemen bleken ook geen moeite te hebben met inhibitie of shifting per se. Ook zij scoorden soms minder goed dan controle kinderen op executieve taken, maar ook deze verschillen bleken een functie van de ongelijkheden die al bestonden op de controle taken, en konden dus niet toegeschreven worden aan verschillen in executief functioneren. Kinderen met een enkelvoudige rekenstoornis hadden echter wel meer moeite met taken waarin inhibitie en shifting gecombineerd moesten worden. Kinderen met lees- en rekenproblemen vertoonden vergelijkbare moeilijkheden. Rekenproblemen lijken dus samen te gaan met deficiënties in het combineren van executieve functies.

In hoofdstuk 4 werden opnieuw executieve vaardigheden onderzocht in kinderen, maar nu in een populatie zonder leerstoornissen. In dit onderzoek stond de vraag centraal of de drie executieve functies inhibitie, shifting en updating als aparte (latente) factoren te onderscheiden zijn in kinderen. Vervolgens werd bekeken hoe de verschillende factoren samenhingen met lees- en rekenvaardigheid, en met verbaal en non-verbaal redeneren. In dit onderzoek werd opnieuw gebruik gemaakt van executieve taken en controle taken, die een beroep deden op benoemsnelheid.

Allereerst creëerde het gebruik van controle taken binnen confirmatieve factoranalyse de mogelijkheid om de non-executieve variantie in de executieve taken te scheiden van de executieve variantie. Nadat de non-executieve variantie was samengebracht onder een benoem-controle factor, bleken factoren voor shifting en updating nog wel onderscheidden te kunnen worden, maar een factor voor inhibitie niet meer. Voorts wees de grootte van de factorladingen uit dat updatingvaardigheid redelijk gemeten kon worden, maar dat het moeilijk is om een goede indicatie te krijgen van shiftingvaardigheid. Ook bleken shifting en updating nauwelijks gecorreleerd, wat betekent dat deze executieve vaardigheden beide detecteerbaar zijn in kinderen, maar onafhankelijk van elkaar opereren.

Van de drie gedetecteerde factoren – de non-executieve factor voor benoemen en de executieve factoren voor shifting en updating – bleek de factor voor benoemsnelheid het hoogst samen te hangen met lees- en rekenvaardigheid. Updating was slechts zwak gecorreleerd met deze schoolse vaardigheden, en de correlaties van shifting met lezen en rekenen bleken verwaarloosbaar. Voorts was updating middelmatig gecorreleerd met non-verbaal redeneren, terwijl benoemen en shifting slecht zwak gecorreleerd waren met deze vaardigheid. Updating en benoemen bleken daarnaast slechts zwak gecorreleerd met verbaal redeneren, terwijl shifting geen verband vertoonde met deze vaardigheid. Naast deze relaties met de factoren, bleek rekenvaardigheid nog specifieke samenhang te vertonen met een taak waarin verschillende executieve functies gecombineerd moesten worden, en een inhibitietaak waarin hoeveelheden benoemd moesten worden.

Door non-executieve variantie te scheiden van executieve variantie vielen de correlaties tussen de executieve functies en lezen, rekenen en vooral redeneren veel lager uit dan verwacht was op basis van eerder onderzoek. Deze resultaten laten zien dat het belangrijk is om te corrigeren voor de invloed van non-executieve taakelementen omdat de relaties tussen executieve functies en andere cognitieve vaardigheden anders overschat worden.

In het laatste hoofdstuk, hoofdstuk 5, werden de resultaten van de drie empirische studies samengevat en bediscussieerd. Concluderend kon gesteld worden dat geen van de drie studies steun heeft opgeleverd voor het idee dat leesvaardigheid gerelateerd is aan de componenten of subroutines van het werkgeheugensysteem. Rekenvaardigheid daarentegen hing positief samen met de vaardigheid om verschillende executieve functies te combineren. Ook hadden kinderen met een specifieke rekenstoornis meer moeite dan kinderen zonder leerproblemen met een taak die beroep deed op het onthouden van dynamische/spatiële visuele informatie. De problemen die kinderen met lees- en rekenproblemen kenmerkten, bleken het best beschreven te kunnen worden als een optelling van de vaak kleine problemen die kinderen met enkelvoudige lees- en rekenstoornissen ondervonden. Tenslotte bleek dat benoemsnelheid, ofwel de vaardigheid om symbolen snel te herkennen en te benoemen, in kinderen zonder leerproblemen gerelateerd was aan lees- en rekenvaardigheid, en dat kinderen met leerproblemen symboolspecifieke benoemproblemen ondervonden. Deze sleutelpositie van benoemsnelheid suggereert dat zowel lees- als rekenvaardigheid afhankelijk zijn van de sterkte, de kwaliteit, en de toegankelijkheid van representaties in het geheugen.

Met betrekking tot de executieve vaardigheden hebben de studies in hoofdstuk 3 en 4 laten zien dat non-executieve taakeisen de prestaties op executieve taken kunnen beïnvloeden. Conclusies aangaande de onderscheidbaarheid van executieve functies worden daardoor bemoeilijkt, evenals conclusies over groepsverschillen in executieve vaardigheden (zeker in populaties die gekenmerkt worden door leerstoornissen), conclusies over de ontwikkeling van executief functioneren, en conclusies aangaande de relaties tussen de executieve functies en andere cognitieve vaardigheden zoals lezen en rekenen. In hoofdstuk 5 werd ook kort stilgestaan bij de vraag hoe leeftijdgerelateerde veranderingen in non-executieve vaardigheden van invloed kunnen zijn op de resultaten van onderzoek naar de ontwikkeling van executief functioneren. Al met al kan geconcludeerd worden dat aanvullende studies naar de validiteit van executieve taken nodig zijn om te achterhalen welke vaardigheden ten grondslag liggen aan prestaties op executieve taken, en derhalve aan de ontwikkeling in prestaties op zulke taken, en relaties tussen deze prestaties en andere cognitieve vaardigheden.

Dankwoord

Allereerst gaat mijn dank uit naar de leerkrachten en kinderen van de volgende scholen die hun medewerking hebben verleend aan de onderzoeken:

de Fransiscus Xaveriusschool, de Ter Cleeffschool, de Dreefschool, de Haarlemse Montessorischool, de St. Bavoschool, de Minister de Leeuwschool, de Prof. J.J. Dumontschool, en de Wim van der Jagtschool in Haarlem, de Fransiscusschool in Bennebroek, basisschool de Pool, de St Aloysiusschool, en de ASVO school in Amsterdam, de Joost van den Vondelschool, de Roald Dahlschool, basisschool het Palet, de Roelof Venemaschool, en de Westwijzer in Amstelveen, de Augustinusschool, de Hoeksteen, en de Wagemakerschool in Landsmeer, en de Blokwhere en de Sint Nicolaasbasisschool in Volendam.

Ook wil ik graag de studenten bedanken die hebben meegeholpen met de dataverzameling:

Nomi Bodor, Marthe Ford, Jeannette Haag, Marjolein Hulshof, Floris Lemmen, Isabel Peters, Najat Rabbae, Sengul Yagmur, Rachna in 't Veld, Carlijn ter Weer, Alexandra Wilson, Annemarie Honig, en Melle van Tricht.

De leden van de leescommissie dank ik hartelijk voor het lezen en beoordelen van het proefschrift.

Mijn promotor Aryan van der Leij wil ik allereerst bedanken voor de mogelijkheid om mijn promotieproject, na een forse wending, onder zijn begeleiding en binnen zijn vakgroep af te ronden. Ook wil ik hem bedanken voor het altijd gul beschikbaar stellen van de middelen (computers, programmatuur, onderzoeksassistentie) zonder welke deze onderzoeken niet hadden kunnen plaatsvinden.

Peter de Jong, mijn co-promotor, dank ik voor alle tijd die hij heeft gestoken in begeleiden en onderrichten. Zijn kritisch houding en uitdagende ideeën maakten het schrijven van dit proefschrift niet altijd makkelijker, maar wel veel interessanter.

Mijn naaste collega's – Rene Reumerman, Roel van Goor, Reinoud Stoel, Eveline Gebhardt, Sandra van Otterloo, Natacha Borgers, en Nijs Lagerweij; jullie aandeel in mijn werkplezier was groot, en zo ook mijn dank.

Mijn ouders, zuster, oma Fie, Rob, en vrienden – Emile Proper, Arnold Jonk, Rogier Verkade, Melissa van Amerongen, Take Vrijlandt, Femke Poppinga, Nimca Zandvliet, Mehdi Dastani, Mattijs Hogeland, HJ Schwencke, dank ik voor hun geduld (AAaahh!!!), humor, en relativering. Alle tafeltennissers en volleyballers, en vooral de dames van D2 – Julia Oei, Mirjam Harthoorn, Ellen Buijn, Sandrijn Wiebenga, Cindy de Visser, Femke Poppinga, Femke Kok, Ieke Wally Nieuwenhout, en coach Raymond Walravens, dank ik voor de welkome afleiding, en het plezier, in en buiten het veld, dat daarmee gepaard ging. (NB. Een proefschrift schrijven is niet moeilijker dan een bal tussen de lijnen / op tafel houden. Dat laatste zal ik in ieder geval nooit leren.)

Femke Poppinga wil ik hartelijk bedanken voor alle tijd die zij gestoken heeft in het ontwerpen van het omslag, en Bram Leenhouts en Henne Proper dank ik heel hartelijk voor het drukken ervan: een prachtig cadeau.

Mijn paranimfijnen Emile Proper en Femke Poppinga dank ik voor het paranimferen.

En Conor: mijn pen is te flets en te doods (Nikolaj Gogol) om me nauwkeurig te kunnen uitdrukken. Maar bedankt voor alles. (Ook voor de kennismaking met Campagnolo STI en Hank Williams sr., natuurlijk.)