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Links between executive functions and early literacy and numeracy

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Citation

Davidse, N. J. (2014, June 25). *Links between executive functions and early literacy and numeracy*. Retrieved from <https://hdl.handle.net/1887/26495>

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Cover Page



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Title: Links between executive functions and early literacy and numeracy

Issue Date: 2014-06-25

Links between Executive Functions
and Early Literacy and Numeracy

Neeltje J. Davidse

**Links between Executive Functions
and Early Literacy and Numeracy**

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op woensdag 25 juni 2014
klokke 13.45 uur

door

Neeltje Joanne Davidse

geboren te Gouda

in 1981

Cover design: Neeltje J. Davidse

Cover photo: © Jolanda Bakker Fotografie, Woerden

Printed by Mostert & Van Onderen, Leiden

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Chapter *1*

General introduction

The general assumption in research on academic development is that delays in early academic skills may have long-lasting effects on learning formal reading, writing, and mathematics (e.g., Duncan et al., 2007; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Muter, Hulme, Snowling, & Stevenson, 2004; Whitehurst & Lonigan, 1998). Although it is claimed that executive functions (EF) are one of the reasons for delays in early literacy and numeracy development (Diamond & Lee, 2011; Duncan et al., 2007; McClelland et al., 2007; NICHD, 2003; Valiente, Lemery-Chalfant, & Swanson, 2010; Welsh, Nix, Blair, Bierman, & Nelson, 2010), research so far has not confirmed this assumption: Research outcomes differ and effects of preschool EF skills on academic skills in the subsequent years are rather small or even non-significant (e.g., Bull, Espy, & Wiebe, 2008; Davidse, De Jong, & Bus, 2013; Diamond & Lee, 2011; Duncan et al., 2007; Kegel & Bus, 2013, 2014; LeFevre et al., 2009; Levy, Gong, Hessels, Evans, & Jared, 2006; McClelland et al., 2007; Welsh et al., 2010). Effects of preschool EF are especially small when controlled for several background variables and moderate to strong effects of early academic skills on later academic development (Kegel & Bus, 2013; Raghubar, Barnes, & Hecht, 2010; Willoughby, Kupersmidt, & Voeger-Lee, 2012). Willoughby et al. (2012) even conclude that there is no causal relation among EF and academic achievement in kindergarten-age. By contrast, Clark et al. (2010, 2013) do find direct relationships between preschool EF and academic achievement at age 5 and 6, even when effects of early academic skills and other background variables are taken into account.

Thus although it is claimed that EF skills are one of the reasons for delays in early academic development (Diamond & Lee, 2011; Duncan et al., 2007; McClelland et al., 2007; NICHD, 2003; Valiente et al., 2010; Welsh et al., 2010), there is no consensus about effects of EF on academic development. In the current thesis the effect of EF on academic development is further explored. It is examined: 1) to what extent EF interferes with benefiting from informal literacy activities that may stimulate early literacy development; 2) whether EF, beyond other general learning skills such as visual-spatial skills and speed of processing, may explain why early literacy and early numeracy skills co-vary substantially. In other words, it is tested whether EF or other general learning skills are essential for numeracy as well as literacy development; 3) whether EF development is *causally* related to academic development from preschool through Grade 1; and 4) whether serious learning impairments such as severe delays in learning math can be explained by delays in EF. This thesis starts with a review on *Executive Functions* (EF), followed by an elaboration of the four research questions.

Executive Functions

EF is an umbrella term for three core cognitive processes that are assumed to be relevant in most academic tasks: Inhibition and attention control, working memory, and cognitive flexibility (Diamond, 2013). Attention regulation gradually improves in typically developing pre-schoolers, for instance by learning to focus on task-relevant aspects and inhibiting non-relevant information or distracters such as noise in the environment. Inhibition and attention control thus seem essential for maintaining on task behaviour, for instance when teacher instructions need to be followed. Working memory helps remembering these instructions and enables performing a task (Davidson, Amso, Anderson, & Diamond, 2006; Diamond, 2013). With increasing age, children are able to remember more information (for instance the number of digits a child can recall improves) and inhibition skills improve, which results in longer sustained attention (Davidson et al., 2006; Diamond, 2013; Gathercole, Pickering, Ambridge, & Wearing, 2004). Brain imaging studies revealed that cerebral networks in the prefrontal cortex are typically activated when tasks strongly appeal to working memory and/ or inhibitory skills (Diamond, 2013). The fact that working memory and inhibitory skills develop well into adulthood can be related to maturation of the prefrontal cortex: The prefrontal cortex has the longest developmental period of all brain areas; only after about 20 years full maturity is reached (Diamond, 2002). As preschool development is central in the current thesis, the focus is on attention/ inhibitory control and memory development, as these core EF skills develop earlier than cognitive flexibility (Davidson et al., 2006).

Impurity is a main problem in studies on EF skills. Other cognitive processes may affect EF skills, which makes it difficult to measure EF skills. Phonological processing for instance may influence performance on the Wisconsin Card Sorting Test, a test often applied when measuring executive functions (Miyake et al., 2000). Moreover some researchers prefer using single tests for measuring sub-skills, whereas others use several tests and make a composite measure (Garon, Bryson, & Smith, 2008). These differences in tasks and scoring methods may explain why there is no consensus about the structure of EF and about best ways for assessing EF (Van der Ven, 2011).

When assessing EF in pre-schoolers, it is essential that tasks are not too complex (i.e., involve not too many operations at the same time as is common for adult EF assessments) (Garon et al., 2008). EF tests used in the current thesis

(digit span forward as the best estimate of working memory, a simple inhibition task in which an automatic response needs to be suppressed, and a simple inhibition task with a long duration in order to measure sustained attention) fit well with an overview of tasks commonly used for measuring working memory and inhibition in pre-schoolers (Garon et al., 2008). The tasks were not too complex or too easy and no bottom or ceiling effects were obtained in the current thesis. Unlike the main stream, we preferred a digit span forward task to a digit span backwards task for assessing working memory, because previous research showed that the digit span backward is too difficult for 4-year olds (e.g., Bull et al., 2008; Kegel & Bus, 2012).

EF in relation to Early Literacy Development

If attention regulation is essential for developing early academic skills, you might for instance expect that children who experience difficulties with ignoring distracters will also have more difficulties with acquiring early literacy skills such as vocabulary and letter knowledge (Lonigan et al., 1999). However, demonstrating that EF is related to early literacy skills does not answer the question which EF skills relate to early literacy development and how these skills interfere. It is well known that informal literacy activities such as shared book reading are a vital incentive for the development of early literacy skills (Levy et al., 2006; Sénéchal, Pagan, Lever, & Ouellette, 2008). Even within low-SES samples, shared book reading has a positive effect on literacy development (Bus, Van IJzendoorn, & Pellegrini, 1995). More specifically, shared storybook reading strongly effects vocabulary development and comprehension, and to a lesser extent code-related knowledge (Mol & Bus, 2011).

As a starting point for the first study, it seemed a plausible hypothesis to assume that children with poor working memory or inhibition may benefit less from shared book reading, resulting in delays in vocabulary and letter knowledge (code-related knowledge). Results of a NICHD study (2003) indeed prove that delays in EF may disrupt the beneficial effects of home activities on literacy development, but effect sizes were small and it was not specified which home activities became less beneficial. In the first study (chapter 2), it was therefore investigated whether effects of shared book reading on vocabulary and letter knowledge are moderated by EF. More specifically it was tested whether children with low EF skills benefit less from shared book reading, and consequently lag behind in early literacy skills.

In order to retrieve a reliable view of how frequently children were read to, a book-cover recognition test was applied in addition to asking the parents about the frequency of shared book reading (Sénéchal, LeFevre, Hudson, & Lawson, 1996). Unlike questionnaires about book reading activities, the book-cover recognition test is not vulnerable for social desirable answers (Sénéchal et al., 1996). Contrary to questions, the book-cover test taps children's actual knowledge about age-appropriate books. An up to date storybook list was composed out of top 100 book sales and library loan numbers, capturing the children's preschool years. In order to avoid false positives due to familiarity with the main character on the cover from television or other sources, three questions tapping into specific book knowledge were asked: "Who is this/who are these"; "What is the name of the story"; and "Can you tell me where the story is about?" Because both a home literacy environment (HLE) questionnaire, including an author recognition test for adults (Cunningham & Stanovich, 1990), and a storybook-cover recognition test were applied, it was also possible to test whether book-cover recognition predicts vocabulary and letter knowledge over and above frequency of shared book reading as reported in the HLE questionnaire and author recognition test for adults. This would imply that the storybook-cover recognition test is indeed a more reliable indicator of shared book reading activities.

For this study, 228 children just starting school in the Netherlands (age range 4;3-4;9) were tested. Spread over six sessions of about half an hour, several early literacy, numeracy, EF, and intelligence skills were assessed.

EF as Explanation for Co-variance among Early Numeracy and Early Literacy Skills

Interestingly, children who lag behind in early literacy often lag behind in early numeracy as well (e.g., Krajewski & Schneider, 2009). This may suggest that equal learning mechanisms or environmental factors underlie both academic domains (Simmons & Singleton, 2008). EF skills might be one of the learning mechanisms underlying both academic domains, as research reports positive correlations among early numeracy and EF (e.g., Espy et al., 2004), and early literacy and EF (e.g., McClelland et al., 2007). Which EF skills cause overlap may, however, depend on which early numeracy and literacy skills are targeted (LeFevre et al., 2010; Purpura et al., 2011). Moreover, it seems likely that other learning mechanisms and experiences may explain the overlap between literacy and numeracy as well. Visual-spatial skills, vocabulary, speed of processing,

and shared book reading are all general factors correlating with both early numeracy and literacy skills (e.g., Davidse et al., 2011; Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003; Furnes & Samuelsson, 2011; Geary 2011; Lefebvre, Trudeau, & Sutton, 2011; Levy, Gong, Hessels, Evans, & Jared, 2006; Purpura, Hume, Sims, & Lonigan, 2011; Rasmussen & Bisanz, 2005). When investigating effects of EF on academic skills, controlling for these other factors is essential, but not commonly done (Raghubar et al., 2010). Using the same dataset as in study 1 (chapter 2), it was tested in this second study (chapter 3) whether early literacy and early numeracy skills co-vary and whether EF skills including working memory and attention control explain co-variance in addition to visual-spatial skills, speed of processing, shared storybook reading, and vocabulary. It was also investigated which of these variables are the most stable and strong predictors of early literacy and early numeracy skills. The focus was on sub-skills of numeracy and literacy, because various sub-skills may depend on different EF skills (e.g., LeFevre et al., 2010; Purpura et al., 2011). The literacy skills were letter knowledge, rhyming, emergent writing, and orthographic knowledge and as indicators of early numeracy skills simple addition and subtraction problems in a non-symbolic (use of checkers for counting) and story context condition were applied. It was investigated whether attention control and working memory explain unique co-variance among early numeracy and literacy skills above visual-spatial skills, speed of processing, vocabulary, and shared book reading.

Causal Relations among EF and Academic Development from Preschool through Grade 1

Long-term effects of EF in preschool on academic development in the subsequent years are hardly investigated or only cover a short period of time (e.g., Clark et al., 2010; Foy & Mann, 2013; McClelland et al., 2007; Welsh et al., 2010). Although researchers claim that EF skills may explain why children lag behind in academic development (e.g., Diamond & Lee, 2011; Duncan et al., 2007; McClelland et al., 2007, NICHD, 2003; Valiente et al., 2010; Welsh et al., 2010), correlations may in fact also imply that if you perform well on numeracy and literacy skills, you automatically develop your EF skills. Studies rarely measured the numerous familial or environmental variables that may confound observed associations. For instance, positive associations between EF and academic skills may be explained in part or in whole by educational style or EF ability

of caregivers. A causal relation among EF and academic skills becomes more plausible when changes in EF over half a year or more are related to changes in academic skills over the same period (Willoughby et al., 2012). Investigating changes in EF is also preferable over assessment of EF at one particular point in time, because EF skills strongly develop between age 5 and 8 (e.g., Davidson et al., 2006; Diamond, 2002). This implies that children who lag behind in preschool EF skills, not necessarily will lag behind in EF in Grade 1. As a result children may not experience difficulties with reading and mathematics in Grade 1 despite underdeveloped preschool EF skills. In order to test causal effects of EF on academic skills, academic and EF skills were tested at the beginning and end of Grade 1. A few schools were not able to participate in the second assessment due to time constraints; the longitudinal analyses are based on 87 children from 7 schools who completed both measurements.

The first goal was testing whether preschool EF (short-term memory and inhibition) is related to math, reading, and writing skills in preschool and subsequently in Grade 1. The risk of obtaining spurious outcomes was reduced by controlling for intervening variables such as educational level of the mother (Willoughby et al., 2012). In the long-term tests, preschool numeracy and literacy skills, both moderate to strong predictors of academic achievement in Grade 1, were also controlled for (e.g., Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Whitehurst & Lonigan, 1998). Due to the small number of schools (7 different schools were involved), Huber-White estimates and a Complex Sample General Linear Model analysis (CSGLM, SPSS 19) were preferred over multilevel analysis.

For testing *causal* relationships among EF development and academic development from preschool through Grade 1, a Fixed Effect Analysis (FEA) was applied in a repeated measure design for EF and academic skills. Fixed Effect Analysis is an alternative for covariate adjustment when evaluating the causal relationship between EF and academic performance. The main advantage of a FEA is that it captures all the measured, but also unmeasured *time invariant* covariates that may cause spurious outcomes, which strengthens conclusions about causality (Kegel & Bus, 2014; Willoughby et al., 2012). When using FEA it is not necessary to measure, or know, the potential confounder variables (Allison, 2009). In a repeated measures design, ideally the same tests are applied at pre- and post-test. However, when capturing development from preschool through Grade 1, it is impossible to apply exactly the same tests, because of bottom and

ceiling effects in both academic and executive skills (Paris, 2005; Paris & Luo, 2010). Testing whether children can solve addition problems up to 20 is for instance useful in Grade 1, but not in preschool. In order to be able to compare repeated measures of EF, numeracy and literacy, all tests were standardized. In this third study (chapter 4), it was tested whether EF development (memory and inhibition) was causally related to academic development (math, reading, and writing) from preschool through first grade.

Can EF be at the Root of Serious Learning Impairments?

The role of EF in the development of serious delays in math or literacy was further explored by means of a case study approach (chapter 5). Two 9-year old monozygotic twin girls were referred to the university clinic because of a severe delay in math development in combination with delays in working memory and visual-spatial skills. This case enabled us to explore to what extent EF skills may underlie a serious delay in math development.

Early numeracy development is based on two numerical systems: A small number system containing only representations for numbers under 4 and an approximate number system (ANS) (Berger, Tzur, & Posner, 2006; Dehaene, 2011; Halberda & Feigenson, 2008; Wynn, 1992). The small number system enables comparing amounts under 4 without counting, referred to as subitizing, which is already evident in 4-5 months old infants (Berger et al., 2006; Wynn, 1992). The small number system is an exact numerical representation system (Dehaene, 2011). The approximate number system (ANS), by contrast, is based on the numerical ratio and develops well into adulthood (Halberda & Feigenson, 2008; Izard, Sann, Spelke, & Streri, 2009): While babies can compare magnitudes with a ratio of 1:2, adults can discover differences with a ratio of 7:8 (Halberda & Feigenson, 2008). Both numerical representation systems seem to have an innate basis, as becomes evident from Wynn's study (1992) showing that typically developing babies know that 1+1 equals 2 and not 1 or 3. Neuroimaging studies show that the IntraParietal Sulcus (IPS) underlies the neuronal code for numerical quantity (Dehaene 2011, Molko et al., 2003; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Combined with counting skills that emerge around the age of 2-3, the ability to recognize small numbers at a glance helps children understanding that every numerical set has a cardinal number. By means of counting numbers under 4, children realize that the final number represents the total amount (Dehaene, 2011). As a result of linking numbers to

quantities children also develop insights in relations among numbers and start understanding that in addition problems such as $3 + 2$ the answer must exceed 3, and, vice versa, in subtraction problems such as $3 - 2$ the answer must be below 3 (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Dehaene, 2011; Duncan et al., 2007; Krajewski & Schneider, 2009). These insights are vital for learning simple sums.

The twins' delay in mathematics was so severe that standardized tests were not sufficient for finding out which core numeracy skills were especially underdeveloped. For testing their knowledge of early numeracy skills such as subitizing, magnitude comparison, and the relations among the numbers 0-10, some paradigms have been reproduced from published sources using E-prime software 2.0.8.90 (Psychology Software Tools, 2013) or MS PowerPoint. Tests were displayed on a 1280 by 1024 resolution screen with a computer running the Windows XP operating system. Using those paradigms, the twins' performance was compared to that of 8 control participants, matched for gender, educational level, and age. A magnitude comparison task was administered using an eye-tracker (*Tobii T120*), which enabled exploring differences in problem-solving by looking at eye-fixations and reaction time per ratio (ratio's ranged from 1:2 to 7:8). Memory load on all tests was compared in order to estimate effects of EF on math problems. As scores on subtests of the WISC-III NL 3rd edition (Wechsler, 2005) tapping into visual-spatial abilities were all significantly below the norm, the role of visual-spatial skills as an alternative explanation of math problems was further explored using number sense tasks with different demands on visual-spatial skills.

For every test, the percentage of correct responses (PCR) and in case of the eye-track tasks, the mean reaction time (RT) for the correct trials was calculated. The presence of a deficit was tested using Crawford and Howell's (1998) modified t-test, which compares the twins' performance with the control group's performance. This technique, specially developed for case studies, enabled us to test whether a single patient is significantly impaired compared to a small control group. Crawford and Garthwaite's (2005) residual standardized difference test (RSDT) permitted us to test the significance of the dissociation between two tasks. For intra-group statistical analyses, paired sample t-tests and linear regressions were applied.

Commonly children with dyscalculia do have some basic number sense knowledge, but as long as skills are not automatized, counting strategies often

need to be applied. The use of counting strategies results in longer processing times compared to typically developing peers (e.g., Kucian et al., 2011; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009). In such cases, number sense training can have a positive effect (Kucian et al., 2011). As the twins' number sense impairment was more severe than in more common cases of dyscalculia, we wondered whether training of core number sense skills would be effective. The twins received an intervention targeting basic number sense skills (Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Wilson et al., 2006). Their responsiveness to this intervention is described in the final part of chapter 5.

In the final chapter it is discussed to what extent EF skills explain delays in early academic development. Highlighted topics are: 1) the strength of the relationship between EF and academic skills; 2) evidence for a causal relationship among EF and academic development, despite the fact that delays in EF at age four are poor predictors of math and reading in Grade 1; 3) the importance of EF compared to other cognitive skills for explaining overlap between numeracy and literacy development; 4) the role of EF in serious impairments in basic numerical understanding; and 5) how useful training of EF is when early academic skills lag behind. The discussion ends with practical implications for early education and suggestions for future research.

Chapter 2

Cognitive and environmental predictors of early literacy skills

Abstract

Not all young children benefit from book exposure in preschool age. It is claimed that the ability to hold information in mind (short-term memory), to ignore distraction (inhibition), and to focus attention and stay focused (sustained attention) may have a moderating effect on children's reactions to the home literacy environment. In a group of 228 junior kindergarten children with a native Dutch background, with a mean age of 54.29 months ($SD = 2.12$ months), we explored therefore the relationship between book exposure, cognitive control and early literacy skills. Parents filled in a HLE questionnaire (book sharing frequency and an author recognition checklist as indicator of parental leisure reading habits), and children completed several tests in individual sessions with the researcher (a book-cover recognition test, PPVT, letter knowledge test, the subtests categories and patterns of the SON, and cognitive control measures namely digit span of the KABC, a peg tapping task and sustained attention of the ANT). Main findings were: (1) Children's storybook knowledge mediated the relationship between home literacy environment and literacy skills. (2) Both vocabulary and letter knowledge were predicted by book exposure. (3) Short-term memory predicted vocabulary over and above book exposure. (4) None of the cognitive control mechanisms moderated the beneficial effects of book exposure.

Published as:

Davidse, N. J., de Jong, M. T., Bus, A. G., Huijbregts, S. C. J., & Swaab, H. (2011). Cognitive and environmental predictors of early literacy skills. *Reading and Writing*, 24, 395-412. doi : 10.1007/s11145-010-9233-3

Introduction

Environmental variables that include parental leisure reading practices and family storybook sharing habits predict early reading skills (e.g., Bus, 2001; Bus, van IJzendoorn, & Pellegrini, 1995; Bracken & Fischel, 2008; Sénéchal, LeFevre, Hudson, & Lawson, 1996). However, not all children benefit from book exposure in preschool age. It is claimed in the literature that individual variation in cognitive control may have a moderating effect on children's reactions to literacy-related experiences (e.g., Bodrova & Leong, 2006). Below we explore therefore the relationship between book exposure, cognitive control and early literacy skills.

The Impact of Book Exposure on Literacy Development

Effects of book exposure on growth in expressive or receptive vocabulary have been demonstrated in a very large number of studies; see the results of several meta-analyses (e.g., Bus et al., 1995; Mol, Bus, de Jong, & Smeets, 2008; Mol, Bus, & de Jong, 2009). The literature also provides support for effects of book exposure on code-related knowledge although findings are more ambiguous (Mol et al., 2008, 2009). Frijters, Barron, and Brunello (2000), for instance, reported that the relationship between frequency of reading books to children and the acquisition of letter-name and letter-sound knowledge depends on the child's level of phonological awareness. In the same vein, Gest, Freeman, Domitrovich, and Welsh (2004) demonstrated that shared book reading was more strongly associated with language comprehension skills (measured by expressive and receptive vocabulary skills and syntax skills) than with print and decoding skills in a sample of children entering kindergarten from low to middle socioeconomic status income families. They stated that this is in line with findings indicating that when reading storybooks to pre-schoolers, parents comment much more frequently on the content of the story than on print concepts. Likewise, research into the time spent on fixating print in storybooks suggests that children do look at print in storybooks, but only for a small amount of time. Evans, Williamson, and Pursoo (2008), for example, found that children aged 36–73 months spent a substantially greater percentage of time looking at the illustrations than at the text. Roughly 6 s of a 2 min reading session was spent on looking at print. Other previous research (e.g., Justice & Ezell, 2002; Levy, Gong, Hessels, Evans, & Jared, 2006) confirms the assumption that children rarely look at print during

storybook reading. Levy et al. (2006) stated therefore that storybook listening at home has little impact on children's understanding of print. According to them, literacy activities focused on print in which the children actively participate are best related to the development of orthographic knowledge, that is, knowing how words look.

Book-Cover Recognition

Questionnaires are often applied to assess characteristics of the Home Literacy Environment (HLE) (e.g., Farver, Xu, Eppe, & Lonigan, 2006; Hood, Conlon, & Andrews, 2008). These questionnaires cover, in addition to family demographics, parental leisure reading habits and family storybook sharing habits. A useful tool to assess parents' exposure to adult literature is an author recognition test (Cunningham & Stanovich, 1990). In the author recognition test, subjects tick actual author names among fictitious names. The number of correct ticks (minus the incorrect ones) appears to be an indicator of parental print exposure. Children's exposure to books is another important HLE indicator (Cunningham & Stanovich, 1990). Cunningham and Stanovich (1990) used a title recognition test for young children as an indicator of book exposure at home. The more books are read to young children, the more titles they may recognize. Likewise, a book-cover recognition test completed by young children may be a proximal measure of their book sharing experiences (Sénéchal et al., 1996). We may expect that when children are more often read to, they are more familiar with the domain of books: They are more able to identify the title, character(s), and the story triggered by the book-cover. Some researchers (e.g., Cunningham & Stanovich, 1991; Sénéchal et al., 1996) have therefore suggested using this measure as an alternative for a questionnaire about family storybook reading habits completed by parents. Stainthorp (1997) however, warned for a risk of obtaining a high score on title recognition due to the fact that in the UK a considerable number of children's books are serialized on British television every year.

If the book-cover recognition test is a better indicator of book exposure, we may expect that the relationship between HLE (parent print exposure checklist and HLE questionnaire) and literacy outcomes (vocabulary and letter knowledge) disappears if we were to control for book-cover recognition. This would imply that the relationship between traditional HLE measures and literacy outcomes is mediated by book-cover recognition. To test this hypothesis, we first assessed whether the HLE questionnaire and the parent print exposure checklist are

related to vocabulary and letter knowledge. Secondly, we tested whether these relationships are mediated by the book-cover recognition test.

The Impact of Child Characteristics on Literacy Development

In addition to HLE, cognitive control measures like inhibition, attention, and memory are expected to have an effect on early literacy skills (Kegel, van der Kooy-Hofland, & Bus, 2009). We used the concept cognitive control as an umbrella term to refer to the ability to hold information in mind (short-term memory), to ignore distraction and to resist making one response and instead make another (inhibition), and to focus attention and stay focused (sustained attention) (e.g., Blair, Zelazo, & Greenberg, 2005; Davidson, Amso, Anderson, & Diamond, 2006; McClelland et al., 2006). To assess short-term memory we applied a digit span task, often referred to as verbal short-term memory or phonological short-term memory (e.g., Alloway et al., 2005; Anthony, Williams, McDonald, & Francis, 2007).

Cognitive control mechanisms are found to be related to vocabulary in preschool and kindergarten years (Carlson & Moses, 2001; Carlson, Moses, & Breton, 2002; Hughes, 1998). McClelland et al. (2007) found that inhibition (as the main component of their Head-To-Toes Task) predicts four-year-olds' vocabulary and print skills, after controlling for various background variables (e.g., gender, age). In addition, they found that children who made greater gains in inhibitory control from fall to spring in their pre-kindergarten year also showed more growth in vocabulary and print skills. This might suggest that inhibition affects how much children benefit from environmental literacy input.

Lonigan et al. (1999) hypothesized that attention and literacy skills are associated prior to formal schooling and attention may be predictive of later reading ability through its effect on early literacy skills. Inattentive children may be less likely to benefit from literacy activities in the home and in (pre) school. The results of Dally's, (2006) longitudinal study are in line with this hypothesis showing that children's attention in kindergarten classrooms (as rated by teachers) had a significant direct influence on first-grade word reading and an indirect influence, through grade-one measures, on second-grade reading comprehension. Inattentive behavior at school entry may thus disrupt the acquisition of early word reading skills. However, it is relevant to note here that parent ratings of children's inattentiveness had no significant associations with reading outcomes and other cognitive control mechanisms (e.g., kindergarten

short-term memory) did not have an impact on reading outcomes in grade one and two.

The literature concerning the influence of short-term memory on literacy is ambiguous. Results of a study conducted by Anthony et al. (2007) are in line with Dally, (2006), who failed to demonstrate a relationship between verbal short-term memory in pre-schoolers and letter- and print knowledge, or word reading at the end of the preschool year. In contrast, Bull, Espy, and Wiebe (2008) found that short-term memory as measured in kindergarten related to reading outcomes at the start of primary school. Likewise, phonological short-term memory scores were uniquely associated with teacher ratings of proficiency in reading measured within 6 weeks of school entry in Alloway et al. (2005). Also, Gathercole, Service, Hitch, Adams, and Martin (1999) showed that in 4-years-olds phonological short-term memory was substantially related to vocabulary ($r = .67$).

In sum, there is some evidence suggesting that cognitive control mechanisms such as short-term memory, inhibition, and attention may be associated with school success from the very start of schooling. However, there is still no explanation as to whether cognitive control is directly related to literacy outcomes, or indirectly (meaning that cognitive control is related to the input children get at home and through that to literacy outcomes). Interestingly, the National Institute of Child Health and Human Development (NICHD) Early Child Care Research Network (2003) demonstrated that family environment predicted children's ability to regulate their attention in the preschool years and that attention processes predicted academic achievement, language development, and social skills. They found that sustained attention and inhibition (as we interpret their impulsivity measure) mediated the relationship between home environment and a composite of letter knowledge and math. Sustained attention also significantly mediated effects of home environment on language skills whereas inhibition did not. In other words, lack of sustained attention and inhibitory control reduced the effect of family environment on outcome measures for school readiness. Findings were statistically significant but effect sizes and mediation statistics associated with them were rather small. In addition, the applied measures did not allow for interpreting which factors in the home environment were mediated by child characteristics and whether mediation effects for letter knowledge were similar to those for vocabulary or math. Leseman, Scheele, Mayo, and Messer (2007), by contrast, demonstrated

that high academic language input at home may compensate for negative effects of low working memory capacity of 4 year olds. Their findings showed that above median academic language input at home can compensate for below median working memory capacity.

As things are, it is still unclear whether preschool children, scoring relatively low on cognitive control, benefit optimally from literacy input in their environment. Furthermore, it is unclear whether the environment can compensate for negative effects of cognitive control variables. The third aim of the present study was therefore to test whether cognitive control moderates the effects of environmental factors on literacy outcomes. To rule out that cognitive control measures assess the same as intelligence tests and not something extra as assumed in the literature (e.g., Diamond, Barnett, Thomas, & Munro, 2007), we tested effects of cognitive control while we controlled for intelligence.

In sum, the main aim of the present study was testing the following hypotheses:

1. Home Literacy Environment (HLE) predicts literacy outcomes: vocabulary and letter knowledge.
2. The relationship between the HLE and literacy outcomes is mediated by children's knowledge of storybooks.
3. Cognitive control moderates effects of HLE on vocabulary and letter knowledge.

Method

Participants

Participants were junior kindergarten children with a native Dutch background in the age range of 4 years and 3 months to 4 years and 9 months. The sample was recruited from 22 randomly selected schools in a province in the western part of the Netherlands. Two of the initially approached schools refused to participate in the project. The schools were attended by Dutch-speaking children from low to middle socioeconomic status families. The study was carried out after parental consent was received. Eight of the children dropped out; one child refused to talk, and seven did not want to participate, resulting in a final sample of 228 participants (117 boys and 111 girls) with a mean age of 54.29 months ($SD = 2.12$ months). We had complete data on $N = 174$ participants (mainly because not all parents returned the questionnaire and/or the author recognition checklist).

Instruments

Spread over six sessions, the participants completed several tests to assess early literacy skills, early numeric skills, intelligence, and cognitive control. The focus in this study was on: intelligence, short-term memory, inhibition, sustained attention, book-cover recognition, receptive vocabulary, and letter knowledge. The parents filled in a HLE questionnaire and an author recognition checklist to assess literacy practices in the home. Intercoder reliabilities were determined for non-standardized tests. Intraclass correlations between two independent coders ranged from .78 (book-cover recognition test) to 1.00 (letter knowledge). Any disagreement was resolved through discussion.

Home Literacy Environment

Parents filled in a HLE questionnaire. The response rate was 85.96%. The survey contained items that related to book sharing. Forty-two parents skipped one or more items, which resulted in a much smaller *N* when we computed a composite measure for items related to book sharing. The item assessing the frequency of book sharing per week (0 = not so often, 1 = every other day, 2 = on a daily basis) was responded to most frequently (*N* = 193) and therefore used in subsequent analyses as an indicator of book sharing frequency. This item correlated significantly with other items related to book sharing: Are you able to read to your child on a daily basis? (*N* = 181; *r* = .67); If you read on a daily basis, do you do that several times a day? (*N* = 163; *r* = .33); Does your child ask you to read a story to him or her? (*N* = 193; *r* = .32). In a meta-analysis, Bus et al. (1995) found similar effect sizes for frequency of book sharing versus a composite measure including other facets of a literacy environment, which indicates that the item assessing the frequency of book sharing per week is a good indicator of book sharing exposure. Furthermore, it is common in the book reading literature to use only one question to assess frequency of shared book sharing (e.g., Farver et al., 2006; Frijters et al., 2000; Gest et al., 2004; Sénéchal et al., 1996).

Checklist on parent print exposure. Parents completed a checklist as a measure of their own exposure to adult literature (response rate 79.82%). The author recognition checklist was composed of 46 authors and 40 foils. We compiled the checklist from top 10 author lists of Stichting Collectieve Propaganda van het Nederlandse Boek (CPNB) [Collective Promotion for the Dutch Book] (CPNB, 2006) from 2004–2006 for the categories Dutch fiction, translated fiction, and crime fiction. All authors with one or more top 10 listings

in these years were selected, resulting in 46 authors. Parents were instructed to tick the authors they knew and to refrain from guessing. The corrected score was obtained by subtracting the number of foils wrongly selected from the number of correctly identified items. Alpha reliability equaled .93.

Book-cover recognition. We used a storybook-cover recognition task completed by the children to account for book exposure experiences across a variety of situations (library, school, and home). Picture story books were selected based on top 100 sales (CPNB, 2006), and library lending numbers from 1999 to 2006 (picture books that were in the top 100 most often borrowed) in the Netherlands. Books that were on both lists were included, resulting in 41 items that differed in familiarity. On a computer screen, children were shown covers of picture books one at a time. Per cover, the experimenter asked the child three questions: “Who is this/who are these?”; “What is the name of the story?”; and “Can you tell what the story is about?” The experimenter coded whether a child was acquainted with the story book or not, thereby taking into account whether the child’s knowledge could be the result of merchandising activities of popular book characters instead of book exposure. The maximum possible score was 41. For example, when a child replied “frog” on seeing the cover of *Kikker en het Vogeltje* [Frog and the Birdsong], but the child could not tell anything about the story, or the story that was told did not match with the one in the book, it was assumed that the child was not acquainted with the book. Frog is a highly merchandized character and just knowing the main character’s proper name did not establish conclusive proof of knowing the story. Alpha reliability equaled .67.

Vocabulary

The Peabody Picture Vocabulary Test-III-NL (Schlichting, 2005), a Dutch version of the PPVT-III (Dunn & Dunn, 1997), was used as an indicator of receptive vocabulary. Participants’ scores were the number of correct items.

Letter Knowledge

Letter knowledge was assessed by having the participants give the name or sound of eight uppercase letters (S, M, K, P, R, O, V, A) and three lower case letters, insofar as lower case form differed from the uppercase form (m, r, a). Each letter was printed on 10 × 10 cm card and shown one at a time. Alpha reliability equaled .90. Due to technical problems in one recording, two items could not be coded; therefore, the percentage of the correctly named (or sounded out) letters was calculated.

Intelligence

The subtests Patterns (copying abstract figures that increase in complexity) and Categories (sorting a pile of 4–6 pictures into two clusters like fruits, vehicles, head gear) of the Snijders-Oomen Nonverbal Intelligence test (SON) (Tellegen, Winkel, Wijnberg-Williams, & Laros, 1998) were selected as indicators of intelligence. Compared to other subtests of the battery, categories loaded highest on the verbal factor of the SON test whereas patterns loaded highest on the nonverbal factor (Tellegen et al., 1998). Factor loadings were .74 and .82, respectively. The patterns and categories subtests correlated significantly ($r = .41$).

Cognitive Control

Short-term memory. The Digit Span Forwards of the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983) was used as indicator of short-term memory. The experimenter says numbers, and the child has to repeat them in exactly the same order. The test started with one practice item of two numbers similar to the first level and increased with one number every next level (three items per level). The subtest was discontinued if a child made an error in two consecutive items of the same level. The score equaled the number of correct responses.

Inhibition. Peg tapping (Diamond & Taylor, 1996) was included as an indicator of inhibition. When the experimenter tapped once, the child had to tap twice and vice versa, thereby inhibiting his or her natural response to mimic the experimenter's behavior. The task consisted of 16 items. Alpha reliability equaled .85. The total score equalled the number of correct responses. Because scores were rather skewed, we performed a median split resulting in a dichotomized variable with children scoring high or low on inhibition.

Sustained attention. Sustained attention was assessed by a subtest of the computerized Amsterdam Neuropsychological Tests (De Sonneville, 2005). Animals appeared one by one in a house on the computer screen. Clicking was only allowed when a cat appeared. The task took about 10 min. Accuracy and response time were registered by mouse clicks. The total score was the number of correct responses minus the number of false alarms and missing items (items for which a child erroneously did not click). Because scores were rather skewed, we performed a median split resulting in a dichotomized variable with children scoring high or low on sustained attention.

Procedure

Parents received a pamphlet with information about the purpose of the project and the procedure (number of sessions, activities during the sessions, etc.). The phone number and e-mail address of the first author were provided in the pamphlet in case parents wished to receive additional information. Parents signed a written consent for participation. All measures were individually administered in a separate room at school by the main researcher or one of twelve trained Bachelor's and Master's students. Testing was spread over six sessions, each lasting for about half an hour. Not all of the results are reported in this article. All sessions were videotaped with a digital camera in a fixed position. Videotaped sessions were used for data coding and for checking whether examiners had followed the scripted protocol. Session order was counterbalanced between participants whereas the order of tasks within a session was fixed. HLE questionnaire and author checklists were sent home including a stamped self-addressed envelope. A cover letter was added with instructions about how to complete the questionnaire and the author checklist.

Results

Descriptive statistics

Descriptive results for all measures are reported in Table 2.1. With two exceptions, continuous variables had a normal distribution (skewness ranging from .03 to .44). The book-cover recognition test and the author recognition checklist were slightly positively skewed (.97 and .80, respectively), but the visual appearance did not demand for transformation (Tabachnick & Fidell, 2007). On SON categories ($M = 10.88$, $SD = 3.00$) and patterns ($M = 9.95$, $SD = 2.78$), our sample's means were similar to the standard population ($M = 10$, $SD = 3$), as reported by Tellegen et al. (1998). On average, children remembered 3–4 numbers ($SD = .90$) of the short-term memory task ($M = 6.52$; $SD = 1.87$), were able to respond correctly 12.36 out of 16 times ($SD = 3.60$) to the inhibition task, and 28.96 out of 240 times ($SD = 32.47$) to the sustained attention task. Mean score on the PPVT-III-NL ($M = 102.46$, $SD = 14.70$) was similar to that of the standard sample ($M = 100$, $SD = 15$). On average children knew two to three letters ($M = 27.44\%$, $SD = 31.94$). Mostly, mothers filled in the HLE questionnaire ($n = 140$), followed by both parents ($n = 41$) and, in rare cases, by the father alone ($n = 14$) or the child's grandparents ($n = 1$). Although all

parents were convinced of the importance of daily book sharing (no variance in this item), not all parents were able to read daily to their child. When asked to rate book sharing frequencies on a weekly basis, 133 parents reported reading every day, while 44 parents reported every other day, and 16 less frequently (not further specified).

On average, parents knew 12.77 authors ($SD = 9.54$) of the 46 on the list; they rarely checked one of the (40) foils ($M = .56$, $SD = 1.22$). Children recognized on average 2.68 ($SD = 2.34$) of 41 book-covers.

Spearman correlations in Table 2.2 are in line with the expectation that book-cover recognition would be related to book sharing frequency and parent print exposure. Of note is that the correlation between book sharing frequency

Table 2.1
Descriptive Statistics for Child and Parent Measures

Variable	N	Median	Range	
Frequency of shared book reading				
How many times do you read to your child per week ^a	193	2.00	0-2	
Variable (max. score)	N	M	SD	Range
Age ^b	228	54.29	2.12	50 – 59
Book-cover recognition (41)	225	2.68	2.34	0 – 8
Parent print exposure (47)	182	12.77	9.54	0 – 40
Cognitive control				
KABC Short-term memory	226	6.52	1.87	2 – 11
Peg tapping (inhibition) (16)	225	12.36	3.60	3 – 16
ANT Sustained attention	228	28.96	32.47	-65 - +80
Literacy Outcomes				
Vocabulary	228	66.24	11.27	39 – 94
Vocabulary ^c	228	102.46	14.70	56 – 144
Letter knowledge ^d	225	27.44	31.94	0 – 100
Intelligence				
SON categories (15)	228	8.60	1.80	5 – 13
SON categories ^c	228	10.88	3.00	1 – 18
SON patterns (16)	228	9.03	1.35	5 – 13
SON patterns ^c	228	9.95	2.78	2 – 16

Note. ^a0 = not so often, 1 = every other day, 2 = on a daily basis. ^bmonths. ^cstandardized scores. ^dmean percentage correct.

and parent print exposure is rather small ($r = .18$). Furthermore, book-cover recognition was significantly correlated with SON categories, SON patterns, inhibition, memory, and sustained attention. SON categories and SON patterns correlated significantly with the cognitive control measures. As expected, vocabulary and letter knowledge were significantly related to book-cover recognition and parent print exposure. Curiously, the frequency of the book sharing item in the questionnaire was correlated with letter knowledge but not with vocabulary. Intelligence and cognitive control measures were significantly related to both vocabulary and letter knowledge (mean $r = .30$, $SD = .06$).

Spearman correlations between cognitive control measures were small to moderate at most (Cohen, 1988), ranging from .26 (short-term memory and inhibition) to .39 (sustained attention and inhibition). We decided to treat them as separate constructs in line with the literature on those measures (e.g. Davidson et al., 2006; Diamond, 2006).

Missing values

The response rate by parents to the questionnaire and parent print exposure checklist was rather high (50%, a criterion introduced by Miller, 1991). Nevertheless the sample reduced from $N = 228$ to $N = 174$ participants. We conducted logistic regressions (McClelland, Acock, & Morrison, 2006) to see if the children that dropped out of the sample due to a missing questionnaire and/or parent print exposure checklist differed from children that were included in subsequent hierarchical regression analyses. None of the logistic regressions revealed a significant effect for missingness, indicating that those who dropped out did not differ from those included in the regression analyses.

Hierarchical Regression Analysis for Variables predicting Vocabulary

To test the three main hypotheses, we carried out a hierarchical multiple regression. In the first step, we entered home literacy environment (frequency of book sharing and parent print exposure checklist). To test whether the relationship between home literacy and vocabulary is mediated by children's knowledge of books, we entered in the second step the book-cover recognition test. In the third step, child cognitive measures (SON subtests and cognitive control measures) were entered, and in the last step the interaction terms between book-cover recognition and dummy-coded cognitive control variables were entered. Continuous predictor variables were centered. As can be seen from

Table 2.2
Spearman correlations between book-cover recognition, environmental factors, child characteristics and literacy outcomes (vocabulary and letter knowledge)

	1	2	3	4	5	6	7	8	9	10.
1. Book- cover recognition	-	.26** (191)	.31** (180)	.29** (225)	.17* (225)	.23** (224)	.15* (222)	.13* (225)	.34** (225)	.39** (222)
2. Frequency of shared book reading per week		-	.18* (179)	-.02 (193)	.02 (193)	-.03 (191)	.02 (191)	.07 (193)	.06 (193)	.20** (192)
3. Parent print exposure			-	.22** (182)	.17* (182)	.17* (180)	.16* (180)	.08 (182)	.16* (182)	.21** (181)
4. SON categories				-	.40** (228)	.28** (226)	.21** (225)	.22** (228)	.38** (228)	.30** (225)
5. SON patterns					-	.24** (226)	.29** (225)	.12 (228)	.31** (228)	.36** (225)
6. KABC short-term memory						-	.31** (223)	.26** (226)	.43** (226)	.32** (223)
7. Peg tapping (inhibition)							-	.39** (225)	.25** (225)	.19** (224)
8. ANT sustained attention								-	.20** (228)	.25** (225)
9. Vocabulary									-	.41** (225)
10. Letter knowledge										-

Note. N's are between brackets. * $p < .05$, ** $p < .01$

the results of Model 1 (see Table 2.3), the parent print exposure checklist was a moderately strong predictor ($b = .18$) and accounted for 3.24% of the variance. The frequency of book sharing was not significant. Under Model 2 in Table 2.3, the parent print exposure checklist test stopped being significant, but book-cover recognition was a strong predictor ($b = .32$). This indicates that the child's book knowledge mediates HLE. Under Model 3, the book-cover recognition test continued to be a significant, albeit weaker, predictor ($b = .22$). SON categories accounted for about 4% of the variance, and memory accounted for an additional 4.84%. The Model fit did not improve after interaction terms (book-cover x cognitive control measures) were entered. None of the three interaction terms caused significant effects. Evidently, children with below median scores and children with above median scores on cognitive control measures benefited equally from book exposure as indicated by the book-cover recognition test.

Table 2.3
Hierarchical Regression Analysis on Vocabulary ($N = 174$)

Variable	Model 1	Model 2	Model 3
<i>Environmental factors</i>			
Parent Print exposure	.18*	.06	-.01
Frequency of Shared Book Reading	-.02	-.08	-.02
Book-cover recognition		.32***	.22**
<i>Child Characteristics</i>			
SON categories			.20**
SON patterns			.10
KABC short-term memory			.22**
Peg tapping (inhibition)			.00
ANT sustained attention			.05
R^2	.03 [†]	.12***	.26***
ΔR^2		.08***	.14***

Note. [†] $p = .07$; * $p < .05$; ** $p < .01$; *** $p < .001$.

Table 2.4
Hierarchical Regression Analysis on Letter Knowledge (N = 174)

Variable	Model 1	Model 2	Model 3
<i>Environmental factors</i>			
Parent Print exposure	.17*	.06	.00
Frequency of Shared Book Reading	.15*	.10	.14
Book-cover recognition		.29***	.23**
<i>Child Characteristics</i>			
SON categories			.03
SON patterns			.21**
KABC short-term memory			.14
Peg tapping (inhibition)			-.00
ANT sustained attention			.15
R ²	.06**	.13***	.24***
ΔR ²		.07***	.11**

Note. * $p < .05$; ** $p < .01$; *** $p < .001$.

Hierarchical Regression Analysis for Variables predicting Letter Knowledge

A second fixed-order hierarchical regression analysis was conducted to test the relationship between predictors and letter knowledge. We followed the same procedure as we did for vocabulary. As can be seen from the results of Model 1 (Table 2.4), frequency of book sharing was a significant predictor ($b = .15$) as well as the parent print exposure checklist ($b = .17$). Under Model 2, the book-cover test was a significant predictor ($b = .29$) and both home literacy indicators stopped being significant. The child's book knowledge evidently mediates the relationship between home literacy environment and letter knowledge. Under Model 3, the book-cover test continued to be significant. It accounted for 5.29% of the variance. SON patterns accounted for 4.41% of the total variance. Interaction terms in Model 4 did not further improve the model fit.

Discussion

Results support the first hypothesis that home literacy environment (as measured by the frequency of book sharing question and the parent print exposure checklist) predicts literacy skills. The results also corroborate the second hypothesis that children's book-cover recognition is an even better

indicator of the literacy environment than home literacy variables (frequency of book sharing and parental print exposure). Third, cognitive control influences literacy outcomes, but it does not strengthen or disrupt the positive influence of book exposure. Specifically short-term memory predicts vocabulary over and above intelligence. In all, the findings support the hypothesis that the book-cover recognition score as indicator of children's literacy environment is a better predictor of literacy outcomes than cognitive measures.

To explain the advantage of the book-cover recognition score over the home literacy measures, we hypothesize that the book-cover recognition test also assesses book sharing experiences in other settings than the home (e.g., in day-care centres, preschools, libraries, or during visits to grandparents). Furthermore, the scale may be less vulnerable to socially desirable answers (Cunningham & Stanovich, 1991; Sénéchal et al., 1996) and less sensitive to non-response and missing items.

The finding that book-cover recognition continues to be a significant, albeit weaker, predictor when intelligence is accounted for supports the suggestion of Sénéchal and colleagues (1996) that intelligence constrains scores on the book-cover recognition test. They argued that children with a better memory may remember more from storybooks than children with lower memory capacities. Therefore, the book-cover recognition test underestimates rather than overestimates children's book exposure. The book-cover recognition test explained 6% of the variance in vocabulary. This is close to what appears from a synthesis of the research (Bus et al., 1995). According to a meta-analysis, about 8% of the variance in vocabulary was explained by preschool book exposure. As far as we know, the only previous study using a book-cover test reported effects beyond this amount: In a study by Sénéchal et al. (1996), about 15% of the variance in receptive vocabulary was explained by book exposure (Experiment 1) which is close to the variance explained in our study without correction for intelligence and cognitive control (11%).

The book-cover recognition test also predicts letter knowledge. Though there are studies that do not reveal effects of book exposure on print knowledge, our findings align with a recent meta-analysis (Mol et al., 2008) showing that print-related skills improve even when the intervention (dialogic reading) targets the story content. Mol and colleagues found that dialogic reading explains about 6.48% of the variance in print related skills which is comparable to our finding (6%). This outcome seems at odds with studies demonstrating that children

hardly pay visual attention to text during storybook reading (e.g., Evans et al., 2008; Levy et al., 2006). To explain this inconsistency, we assume that a small amount of time preschool children spent on looking at print during book reading may be enough to learn about print. Even when eye fixations on print are brief, the sum total may result in growth of print knowledge (Justice, Pullen, & Pence, 2008).

Consistent with previous research (Leseman et al., 2007; Sénéchal et al., 1996), we found that short-term memory is significantly correlated with vocabulary. Evidently, this cognitive control measure assesses skills over and above intelligence (Diamond et al., 2007). It is noteworthy that none of the other cognitive control measures contributed to vocabulary after controlling for intelligence. Unlike the results of the NICHD Early Child Care Research Network study (2003) in which sustained attention explained differences in a composite measure of letter knowledge and math, we did not find effects of cognitive control on letter knowledge. It could be that cognitive control is more important in math than in letter knowledge, explaining the difference with the NICHD study.

There is no support for the hypothesis that cognitive control mechanisms, that is, short-term memory, inhibitory control, and sustained attention, moderate learning from book exposure as was suggested by McClelland et al. (2007). Our study shows, on the contrary, that all children profit from book sharing whatever their cognitive control skills. Probably because book reading sessions are highly structured, cognitive control skills do not moderate effects of book exposure on literacy outcomes. We hypothesize that cognitive control mechanisms might gain in importance as children practice more on their own as for instance occurs when children complete computer tasks (Kegel et al., 2009).

Limitations and Future Directions

Because the present study is correlational in nature, prudence is called for conclusions concerning causal relationships. Book exposure may cause vocabulary growth and growth in print knowledge, but can also be the outcome of increase in vocabulary and print knowledge or reflect the interactive nature of book sharing and literacy skills (e.g. Crain-Thoreson & Dale, 1992; Justice, Chow, Capellini, Flanigan, & Colton, 2003; Raikes et al., 2006). If children have more vocabulary, or a better developed print knowledge, they might show more interest in storybooks, thereby improving vocabulary and letter knowledge.

Although we showed that variance in book-cover recognition was predicted by environmental factors, it still is the child who completed the test. We showed that intelligence and cognitive control hardly influenced performance, but we cannot rule out the possibility that child characteristics not measured in the current study may play a role.

So far, there is no evidence for differential effects of book exposure between children who differ in cognitive control. We cannot rule out that in spite of the large number of participants the sample was too homogeneous. The influence of child characteristics on school readiness should be explored in less homogeneous groups with more children scoring low on cognitive control (Kegel et al., 2009).

Due to our rather homogeneous sample, variance in the question about book sharing frequency was limited (69% reporting reading every day). This may also explain the rather low correlation between book sharing frequency and the parent print exposure checklist ($r = .16$) and the non-significant relationship between book sharing frequency and vocabulary.

It seems more plausible to hypothesize that cognitive control might gain impact when learning capitalizes more on self-regulating capacities as is the case from Grade 1 and up. Altemeier, Abbott, and Berninger (2008) for example, found that cognitive control at the beginning of Grade 1 was related to children's reading development in Grade 1. A basic skill in learning to read is decoding (mapping of letters and sounds) which strongly appeals to cognitive control skills: letters and sounds need to be connected and memorized and afterwards the sounds need to be combined in order to be able to pronounce the word. Children with weak cognitive control skills may have difficulties carrying out this series of tasks (see also: Savage, Cornish, Manly, & Hollis, 2006).

Implications

One main result of the current study is a new instrument—the book-cover recognition test—as a proximal measure of children's book exposure in research and individual assessments of children's literacy environment. The findings are in line with the hypothesis that exposure to books is an important step in becoming literate. Book exposure correlates not only with vocabulary but with code-related knowledge as well. The results also support the hypothesis that book sharing is beneficial for all children. So far, there is no evidence for the hypothesis that effects of book exposure depend on child characteristics such as cognitive control skills.

Chapter 3

Explaining common variance shared by early numeracy and early literacy

Abstract

How can be explained that early literacy and numeracy share variance? We specifically tested whether the correlation between four early literacy skills (rhyming, letter knowledge, emergent writing, and orthographic knowledge) and simple sums (non-symbolic and story condition) reduced after taking into account preschool attention control, short-term memory, speed of processing, visual-spatial skills, vocabulary, and shared book reading. 228 Dutch native pre-schoolers (mean age 54.25; $SD = 2.12$ months) participated. The results revealed that 1) all literacy skills were related to sums (non-symbolic and story condition), 2) rhyming was the strongest predictor of non-symbolic sums, and letter knowledge of sums in story context, 3) visual-spatial skills explained part of the shared variance in the non-symbolic condition and visual-spatial skills, vocabulary and short-term memory explained part of the shared variance in sums in story context. Implications for the preschool curriculum and early interventions are discussed.

Published as:

Davidse, N. J., de Jong, M. T., & Bus, A. G. (2014). Explaining common variance shared by early numeracy and early literacy. *Reading and Writing*, 27, 631-648. doi : 10.1007/s11145-013-9465-0

Introduction

Young children with delays in early literacy skills are often also delayed in early math skills (Krajewski & Schneider, 2009) which might mean that early literacy and numeracy share variance (Simmons & Singleton, 2008). Early literacy skills typically encompass skills like phonological awareness, orthographic knowledge, letter knowledge, vocabulary, and emergent writing skills (Muter, Hulme, Snowling, & Stevenson, 2004; Whitehurst & Lonigan, 1998), and early numeracy, skills like subitizing, magnitude comparison, counting skills, number knowledge, ordinality, and cardinality (Halberda & Feigenson, 2008; Jordan, Kaplan, Nabors Ola 'h, and Locuniak, 2006; Krajewski & Schneider, 2009). Early literacy skills are all rather strong predictors of how successful children will be in learning to decode (Muter, Hulme, Snowling, & Stevenson, 2004; Whitehurst & Lonigan, 1998). Early numeracy skills may facilitate insights in relations among numbers and enable solving simple sums (e.g., Dehaene, 2011; Halberda & Feigenson, 2008). Research revealed varying co-morbidity percentages among math and literacy; percentages range from 11 to 56 % for children with reading problems who also have arithmetic problems, and from 17 to 70 % in the case of children with arithmetic problems also having reading problems (Landerl & Moll, 2010).

This study aimed at highlighting the covariation between early literacy and numeracy whereby we targeted extraneous as well as intrinsic factors. From the literature appears for instance, that shared storybook reading benefits early literacy (e.g., Davidse, de Jong, Bus, Huijbregts, & Swaab, 2011; Mol & Bus, 2011; Sénéchal, Pagan, Lever, & Ouellette 2008) as well as early numeracy, which may be stimulated by storybook reading conversations about size, shape, and number (e.g., Anderson, Anderson, & Shapiro 2005; LeFevre et al., 2009; Van den Heuvel- Panhuizen & Van den Boogaard, 2008). Book reading may thus be a stimulus for both early literacy and numeracy. On the other hand, early literacy and numeracy may both appeal to the same cognitive abilities. For instance, visual-spatial skills may play an important role in both early literacy (e.g., Alloway et al., 2005; Brunswick, Martin, & Rippon, 2012; Bull, Espy, & Wiebe, 2008; Davidse et al., 2011) and numeracy skills (e.g., Assel, Landry, Swank, Smith, & Steelman, 2003; Bull et al., 2008; Duncan et al., 2007; Krajewski & Schneider, 2009; Murphy, Mazzocco, Hanich, & Early, 2007; Rasmussen & Bisanz, 2005), and might explain why literacy and numeracy overlap. The current study explores

shared book reading and general cognitive skills such as visual-spatial skills as explanations for the co-variance among early literacy and early numeracy skills. For all selected factors, the literature reports significant correlations with literacy and numeracy (Simmons & Singleton, 2008).

Which Early Literacy Skills correlate with Math Skills?

Medium to large correlations among phonological awareness and numeracy skills are reported (e.g., Alloway et al., 2005; De Smedt, Taylor, Archibald, & Ansari, 2010; Kleemans, Peeters, Segers, & Verhoeven, 2012; Krajewski & Schneider, 2009; Simmons, Singleton, & Horne, 2008) although there are also null-results (see Purpura, Hume, Sims, & Lonigan, 2011). Phonological skills may be important for math development because certain arithmetical tasks appeal to the use of verbal codes (Dehaene, Piazza, Pinel, & Cohen, 2003; Simmons & Singleton, 2008). Consequently, phonological skills are related to verbal counting and arithmetic fact retrieval (i.e., small additions and subtractions), that rely on the verbal representation system, but phonological skills are not (or to a lesser extent) related to math tasks that rely on procedural strategies such as large subtractions, to untimed measures of general math achievement, or to non-symbolic math tasks like estimation (Dehaene & Cohen, 1995; De Smedt et al., 2010; Geary, Hoard, Nugent, & Bailey, 2012; Simmons & Singleton, 2008). In fact, the non-symbolic representation system of approximate quantities is assumed to be distinct from the verbal system and reveals lower correlations with phonological skills (Dehaene & Cohen, 1995).

The correlation of math development with print knowledge is mostly smaller than the correlation with phonological awareness (e.g., LeFevre et al., 2010; Purpura et al., 2011). Print knowledge refers to the ability to recognize print among other forms and basic print conventions such as the reading/spelling direction (i.e., knowing that for instance in Dutch, words are spelled and read from left to right) (Whitehurst & Lonigan, 1998). Print knowledge may be related to aspects of math development such as familiarity with written Arabic numbers (i.e., knowing that the symbol '3' refers to an amount of three). Likewise, applying non-numerical symbols like + and – appeals to knowledge about the mathematical print system (i.e., knowing that + means adding and – means subtracting) (Purpura et al., 2011). Moreover, number and letter naming are highly correlated in preschool (Piasta, Purpura, & Wagner, 2010), probably because distinguishing letters from numbers is a first step in learning letters and numbers.

Effects of General Cognitive Abilities

Several general cognitive skills may explain why early numeracy and early literacy co-vary. Recognizing and memorizing visual forms is important in memorizing letters and orthographic features (Levy, Gong, Hessels, Evans, & Jared, 2006) as well as in comparing amounts and solving simple sums (Assel, Landry, Swank, Smith, & Steelman, 2003; Rasmussen & Bisanz, 2005), which may explain why visual-spatial processing relates to early literacy and numeracy. Visual-spatial skills relate to early literacy because early in the reading development, words are recognized based on their visual shape (Levy et al., 2006). Accordingly, numerical symbols (e.g., 4, 5) are also distinguished by means of their visual-shape (Dehaene, 2011). Moreover, when counting, young children often use fingers or other objects, or they visualize objects (i.e., make a mental representation of objects), processes that rely on visual-spatial skills (Assel et al., 2003; Rasmussen & Bisanz, 2005).

Vocabulary is correlated with all the literacy measures included in the current study (Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003) as well as with math development (Purpura et al., 2011; Seethaler, Fuchs, Fuchs, & Compton, 2012). Purpura et al. (2011) reported moderate to strong correlations among vocabulary and several early numeracy skills like verbal counting and story problems. Verbal counting appeals to the use of number words, thus to vocabulary. Moreover, a certain vocabulary is necessary for extracting relevant numerical information from a story (Fuchs et al., 2006), and when using words as more, less, big, small (Anderson, et al., 2005; LeFevre et al., 2009; Van den Heuvel-Panhuizen & Van den Boogaard, 2008). Vocabulary growth is moderately to strongly related to the development of phonological awareness: The more extended children's vocabulary, the better young children perform on phonological awareness tasks (Metsala, 1999).

Likewise, the speed with which human infants process information (Weiler, Forbes, Kirkwood, & Waber, 2003), is found to relate to early literacy (e.g., Furnes & Samuelsson, 2011; Lewis et al., 2011) as well as to early numeracy and further math development (Cirino, 2011; Geary, 2011). Children delayed in acquiring early numeracy or literacy skills often have processing speed needs, as becomes evident from difficulty in performing simple cognitive tasks fluently and automatically (Weiler et al., 2003).

Another plausible hypothesis is that executive skills such as short-term memory and attention control (Davidson, Amso, Anderson, & Diamond, 2006;

Diamond & Lee, 2011) explain co-variation as both affect early numeracy (e.g., Espy et al., 2004; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009) and early literacy skills (e.g., Davidse et al., 2011). Children with lags in executive skills run the risk of missing beneficial effects of essential experiences, the result being that children may lag behind in early literacy (Kegel & Bus, 2013) and early numeracy skills (Diamond & Lee, 2011). The working memory component of EF (Diamond, 2013) enables holding information in mind (such as the number of dots in a number comparison task), and inhibitory control is needed to repress the impulse to respond to the most salient aspect such as size of objects or configuration (Blair & Razza, 2007). Without these skills children may not be successful in solving simple tasks thereby acquiring new skills.

If these domain-general factors (visual-spatial skills, vocabulary, speed of processing and EF) affect academic learning from an early age, control for those factors may weaken the correlation between early literacy and early numeracy skills (Simmons & Singleton, 2008). There is indeed some evidence of reduced relations among early numeracy and literacy due to these general abilities. For instance in the study of Krajewski and Schneider (2009), the significant relation ($r = .51$) between phonological awareness and early numeracy skills like comparing magnitudes (i.e., knowing that five is more than three) and insights in relations among numbers (i.e., the difference between two numbers is another number), became non-significant after controlling for significant effects of visual-spatial skills. Likewise after controlling for working memory, phonological awareness was no longer significantly related to counting, adding and subtracting up to 10 (Alloway et al., 2005). On the other hand, not all relevant studies reveal the same results: Kleemans et al. (2012) found that after controlling for working memory and visual-spatial skills, phonological skills still accounted for variation in a composite measure of early numeracy. The inconsistency in outcomes may be due to the fact that Alloway et al. (2005) controlled for external factors such as maternal education and number of years in preschool, whereas Kleemans et al. (2012) did not take background variables into account that may affect early literacy and numeracy.

In sum, the common variance shared by early numeracy and literacy may reduce after controlling for effects of general abilities (Simmons & Singleton, 2008). In other words, general abilities that relate to both early numeracy and early literacy may thus explain why numeracy and literacy co-vary substantially.

Effects of Home Activities

Next to general abilities, shared book reading relates to both early numeracy and early literacy (e.g., Lefebvre, Trudeau, & Sutton, 2011; Mol, Bus & de Jong, 2009) and consequently may reduce the common variance shared by early numeracy and literacy. Letter knowledge (Mol et al., 2009) and phonological awareness (measured with rhyming, initial consonant comparison, syllable segmentation, and syllable deletion) for instance can be enhanced by shared book reading (Lefebvre et al., 2011). Similarly, mathematical talk and mathematical thinking is stimulated by shared storybook reading (Anderson et al., 2005; Van den Heuvel-Panhuizen & Van den Boogaard, 2008). A coding scheme was used which arranged utterances by the child for instance by number-related utterances such as resultative counting (i.e., mentioning/understanding that the final number represents the total amount) and using ordinal numbers (Van den Heuvel-Panhuizen & Van den Boogaard, 2008). Results are based on the number of utterances assessed in each domain. Mathematical talk involves using words as big or small (size), bigger than (when comparing objects), how long (referring to length or time), lots and tons (approximation), and the ball is round (referring to shape). Anderson et al. (2005) found that the amount of mathematical talk differed among storybooks and families. For eliciting mathematical thinking, however, it does not matter whether a storybook is written with the specific purpose of mathematical instruction or not (Van den Heuvel-Panhuizen & Van den Boogaard, 2008). LeFevre et al. (2009) also reported direct effects on formal mathematics: The more storybook reading the better children performed on simple addition sums.

In all, by means of shared storybook reading, using a variety of storybooks, the development of early numeracy skills as well as literacy skills can be supported. In other words, the relation between early numeracy and literacy might weaken when controlling for shared storybook reading.

Present Study

In sum, there is evidence that the co-variance among early numeracy and literacy skills results from general cognitive processes or experiences that are assumed to affect both (Geary et al., 2012; Simmons & Singleton, 2008). Despite the need of simultaneous control of factors that influence both (Geary et al., 2012), most studies testing co-variation of early literacy and math development did not consider the role of book reading activities, EF skills, visual-spatial skills, speed

of processing, and vocabulary. The main goal of the current study was therefore testing whether these variables may explain unique co-variance among early numeracy (simple sums) and early literacy. We also test which variables are the most stable and strong indicators for a variety of early literacy and numeracy skills (e.g., Krajewski & Schneider, 2009; LeFevre et al., 2010; Purpura et al., 2011; Simmons, Singleton, & Horne, 2008). By controlling for all other potential indicators we estimate the unique variance for each factor measured in this study. We used rhyming, letter knowledge, orthographic knowledge, and emergent writing as indicators of early literacy and simple addition and subtraction sums in a non-symbolic and in a story context as indicators of early numeracy. The study was conducted among pre-schoolers to specify which skills in particular need attention in preparation of instruction in first grade (Duncan et al., 2007) and how supportive literacy experiences are for math experiences and vice versa.

Method

Participants

228 Dutch native pre-schoolers (117 boys and 111 girls) with a mean age of 54.25 ($SD = 2.12$ months) participated in the study. The sample was recruited from 22 randomly selected schools in the Western part of the Netherlands. The preschool curriculum in the Netherlands involving four-year-olds is not yet focused on emergent literacy and numeracy. The schools were attended by Dutch-speaking children with a low to middle socioeconomic background. The main stream of parents had a degree in intermediate or higher vocational education (58.10 % of the mothers and 54.40 % of the fathers). Of the mothers, 31.40 % only finished primary or secondary school, compared to 29.00 % of the fathers. 10.50 % of the mothers and 16.60 % of the fathers had a university degree. All parents gave informed consent for participation.

Instruments

Early Literacy Skills

Letter knowledge. On a computer screen, children were shown in succession eight uppercase letters (S, M, K, P, R, O, V, A) and three lower case letters, insofar as lower case form differed from the uppercase form (m, r, a). Each letter was visible during 4 s. Children were instructed to give the name or sound of each letter as soon as possible. The score equaled the number of correct responses (max score is 11). Alpha reliability equaled .90.

Rhyming. On a computer screen one picture appeared (for example a picture of a hand), and simultaneously the question: “Which word rhymes with hand [Dutch word for hand]?” is read aloud by the computer. Next three pictures appeared in succession and simultaneously the name of the object was read aloud (for example, kast, mand, vaas [cupboard, basket, vase]). The child had to name or point to the rhyming word (in this example mand [basket]). One practice trial and 10 test trials were presented. The score equaled the number of correct responses (max score is 10). Alpha reliability equaled .84.

Emergent writing. Children were asked to write down their proper name and the words mama, fire, cheese, wheel, and boot. The writings were scored based on a scale ranging from 0 (scribble produced by scratching) to 13 (conventional spelling); see Levin, Both-de Vries, Aram, & Bus (2005) for a detailed description. The writing scores were summed, resulting in a maximum score of 78. Alpha reliability equaled .90.

Orthographic knowledge. This task was adapted from Levy et al. (2006). Children had to recognize the correct orthography among pairs consisting of a correctly spelled word and the same word containing a violating of a spelling convention. A total of 12 spelling conventions were tested: A scribble, spacing in the word, a word written upside down, one of the letters replaced by a number, a picture instead of a written word, only vowels, only consonants, letter-like characters, a word written backwards, the use of capitals in the word, repeating the first letter of the word (e.g., sss), and violation of linearity. The stimuli pairs appeared on a computer screen, one at a time. The child was asked to point to the correctly spelled word. After responding, the next trial was presented. This task consisted of a total of 87 items (and 2 practice items). Alpha reliability equaled .80. The score equaled the number of correct responses (maximum score was 87). Alpha reliability equaled .84.

Early Numeracy Skills

Addition and subtraction sums: Non-symbolic and story context condition. This task was adapted from Jordan et al., 2006. In the non-symbolic condition, children were able to use material (checkers) to solve the sums. The experimenter said for example: “Look, I have two stones. Now I’m covering them. Look carefully, I’m adding one stone. How many stones do I have now? Show it to me by using your stones and then tell me the number.” The addition as well as the subtraction sums had one practice item where the experimenter

corrected the child if needed. A total of four addition ($2 + 1$; $4 + 3$; $2 + 4$; $3 + 2$) and four subtraction sums ($3 - 1$; $7 - 3$; $5 - 2$; $6 - 4$) were used.

In the story context condition, exactly the same sums were done, but this time in a story context. Children were not allowed to use the checkers to solve the sums. The experimenter asked for example: “Mary has six bananas, Joe takes away four bananas. How many bananas does Mary have now?”

Control Variables

Book-cover recognition. A storybook-cover recognition task was used as indicator of book exposure experiences across a variety of situations (library, school, and home) (Davidse et al., 2011). Picture storybooks were selected based on top 100 sales lists from the Stichting Collectieve Propaganda van het Nederlandse Boek (CPNB) [Collective Promotion for the Dutch Book] CPNB, 2006), and library lending numbers from 1999 to 2006 (picture storybooks that were in the top 100 most often borrowed) in the Netherlands. Books that were on both lists were included, resulting in 41 items that differed in familiarity. On a computer screen, children saw covers of picture storybooks one at a time. Per cover, the experimenter asked the child three questions: “Who is this/who are these?”; “What is the name of the story?”, and “Can you tell what the story is about?” Based on these answers, the experimenter coded whether a child was acquainted with the story book or not. The maximum possible score was 41. For example, when a child replied “frog” on seeing the cover of *Kikker en het Vogeltje* [Frog and the Birdsong], but the child could not tell anything about the story, or the story that was told did not match with the one in the book, it was assumed that the child was not acquainted with the book. Frog is a highly merchandized character and just knowing the main character’s proper name did not establish conclusive proof of knowing the story. Alpha reliability equaled .67.

Executive skills: Short-term memory. The Digit Span Forwards of the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983) was used as indicator of short-term memory. Numbers needed to be repeated in exactly the same order. The test started with one practice item including two numbers similar to the first level and increased with one number every next level (three items per level). The test consisted of 19 items and was discontinued if a child made an error in two consecutive items of the same length. The score equaled the number of correct responses.

Executive skills: Attention control. For attention control three subtests of the computerized Amsterdam Neuropsychological Tasks [Amsterdamse Neuropsychologische Taken; De Sonneville, 2005] were applied. In the GONOGO task, two different abstract figures appeared randomly on the computer screen during about 2 min. Clicking was only allowed when one of the two figures appeared. In the Sustained Attention task, during about 10 min animals appeared in a window of a house (one at a time). Children were allowed to click, but only when a cat was visible. In the Memory Search Object task level 1, four different animals appeared in the windows of a house. Clicking was only allowed when one of the four animals was a mouse. The task took about 2 min. Accuracy and response time were automatically registered. Total score per task was the number of correct responses minus the number of false alarms and missing items (items where a child erroneously did not click). Confirmatory factor analysis on the three tests of attention control revealed one factor, explaining 64.07 % of the variance with factor loadings of .84, .85 and .70, respectively (Tabachnick & Fidell, 2007), therefore this composite measure was used.

Visual-spatial skills. The standardized subtest Patterns of the Snijders-Oomen Nonverbal Intelligence test (SON) (Tellegen, Winkel, Wijnberg-Williams, & Laros, 1998) was selected as indicator of visual-spatial skills: Copying abstract figures of increasing complexity while they remained present.

Speed of processing. The subtest picture naming of the Rapid Automatized Naming test (Van den Bos, Lutje Spelberg, & Ruizeveld-de Winter, 2008) was used. As quickly as possible, children had to name pictures of a bike, a duck, a tree, pair of scissors, and a chair that all appeared repeatedly on a sheet, randomly divided in 5 rows. The response time in milliseconds per item was calculated by dividing the total response time by the number of named pictures (total of pictures minus omissions). Hardly any errors were made, therefore errors were not taken into account (Van den Bos et al., 2008).

Vocabulary. The Dutch version of the PPVT-III, the Peabody Picture Vocabulary Test-III-NL (Schlichting, 2005), was used as an indicator of receptive vocabulary.

Participants’ scores were the number of correct items.

Results

Correlations

In Table 3.1 the descriptive statistics for all measures are displayed. All literacy variables correlated significantly with addition and subtraction sums, non-symbolic and in story context (see Table 3.2). Rhyming correlated with sums in story context ($r = .34$) and non-symbolic sums ($r = .32$). Letter knowledge was the strongest literacy correlate of sums in story context ($r = .39$). The control variables short-term memory, visual-spatial skills, attention control, and vocabulary correlated significantly with both types of sums and with all four literacy measures. Speed of processing correlated with both types of sums and with letter knowledge, rhyming, and emergent writing, but not with orthographic knowledge. Shared storybook reading correlated significantly with all four literacy measures and with sums in the non-symbolic and story context. In all, this implies a substantial overlap among achievement in early numeracy and literacy.

Table 3.1

Descriptive statistics

Variable	Min	Max	mean	SD
Nonsymbolic sums (percentage correct)	0	100	40.82	20.23
Sums in story context (percentage correct)	0	100	28.43	19.92
Rhyming	1	10	7	2.92
Letter knowledge	0	10	2.73	3.18
Orthographic knowledge	27	86	51.39	11.15
Emergent writing	10	71	42.93	14.11
Shared storybook reading	0	8	2.67	2.33
Short-term memory	0	11	6.50	1.93
Attention control (factor score)	-3	2	0	1
Speed of processing (milliseconds)	45000	422500	105608.41	40983.30
Visual-spatial skills	5	13	9.03	1.35
Vocabulary	33	105	66.28	11.52

Regression Analyses

First a series of hierarchical regression analyses was carried out to test whether rhyming, letter knowledge, orthographic knowledge, and emergent writing

Table 3.2
Pearson correlations among variables

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. Sums: Nonsymbolic context	-	.33***	.25***	.32***	.22**	.18**	.13*	.22**	.21**	-.17*	.33***	.18**
2. Sums: Story context		-	.39***	.34***	.24***	.23**	.15*	.29***	.24**	-.18**	.28***	.34***
3. Letter knowledge			-	.41***	.35***	.43***	.37***	.31***	.30***	-.19**	.31***	.36***
4. Rhyming				-	.33***	.36***	.28***	.40***	.44***	-.22**	.36***	.53***
5. Emergent Writing					-	.28***	.17**	.23***	.39***	-.14**	.51***	.29***
6. Orthographic knowledge						-	.19**	.24***	.28***	-.02	.26***	.32***
7. Shared storybook reading							-	.21**	.12	-.03	.20**	.35***
8. Short-term memory								-	.29***	-.15*	.26***	.39***
9. Attention control									-	-.33***	.28***	.26***
10. Speed of processing										-	-.14*	-.15*
11. Visual-spatial skills											-	.29***
12. Vocabulary												-

Table 3.3
Predicting nonsymbolic sums with rhyming and letter knowledge

Variable	Model 1 (β -values)	Model 2 (β -values)	Variable	Model 1 (β -values)	Model 2 (β -values)
Rhyming	.32***	.22*	Letter knowledge	.24***	.10
Shared storybook reading		.03			.01
Short-term memory		.08			.09
Attention control		.02			.07
Speed of processing		-.09			-.09
Visual-spatial skills		.21**			.23**
Vocabulary		-.07			.01
R^2	.10***	.16***		.06***	.15***
ΔR^2		.06*			.09**

Note. * $p < .05$; ** $p < .01$; *** $p < .001$.

Table 3.4
Predicting nonsymbolic sums with emergent writing and orthographic knowledge

Variable	Model 1 (β -values)	Model 2 (β -values)	Variable	Model 1 (β -values)	Model 2 (β -values)
Emergent writing	.21**	.02	Orthographic knowledge	.17*	.05
Shared storybook reading		.03			.03
Short-term memory		.10			.11
Attention control		.08			.09
Speed of processing		-.09	Not included ^a		
Visual-spatial skills		.23**			.24**
Vocabulary		.02			.006
R^2	.04**	.13***		.03*	.13***
ΔR^2		.08**			.10***

Note. * $p < .05$; ** $p < .01$; *** $p < .001$; a. did not correlate with orthographic knowledge.

each predicted sums in pre-schoolers. In the next step of the regression, control variables were entered to test whether effects of literacy skills reduced after controlling for preschool regulatory skills (short-term memory and attention control), visual-spatial skills, speed of processing, vocabulary, and shared storybook reading. A reduction of the correlation with letter knowledge to non-significance means that the substantial co-variance among early literacy and numeracy can be explained by significant effects of one or more control variables (see Table 3.3). Effects of control variables indicate unique variance given that we entered all control variables simultaneously. When orthographic knowledge was the literacy predictor, speed of processing was not included as control variable since it did not correlate significantly with orthographic knowledge.

Non-Symbolic Sums. All four literacy tasks uniquely related to non-symbolic sums (see Tables 3.3, 3.4). Rhyming was the strongest correlate among the literacy skills (see Tables 3.3, 3.4). The effects of all literacy skills substantially reduced after preschool short-term memory, attention control, visual-spatial skills, speed of processing, vocabulary and shared storybook reading were taken into account (see Tables 3.2, 3.3). Only rhyming remained a significant predictor after entering the control variables. Visual-spatial ability was the only significant predictor among the control variables, meaning that this variable explained unique variance in the overlap between literacy and numeracy.

Sums in Story Context. The results revealed that all four literacy tasks uniquely predicted sums in story context (see Tables 3.5, 3.6). Letter knowledge was the strongest correlate among the literacy skills, followed by rhyming (see Tables 3.4, 3.5). The effects of the literacy skills significantly reduced after preschool short-term memory, attention control, visual-spatial skills, speed of processing, vocabulary and shared storybook reading were taken into account (see Tables 3.5, 3.6). Letter knowledge continued to be a significant predictor, whereas the effects of rhyming, emergent writing and orthographic knowledge reduced to non-significance. Of all control variables, visual-spatial skills and vocabulary were significant predictors and short-term memory was a marginally significant predictor (with the exception that visual-spatial skills did not significantly relate to sums in story context when emergent writing was a predictor; $p = .08$).

Table 3.5*Predicting sums in story context with rhyming and letter knowledge*

Variable	Model 1 (β -values)	Model 2 (β -values)	Variable	Model 1 (β -values)	Model 2 (β -values)
Rhyming	.33***	.09	Letter knowledge	.38***	.25**
Shared storybook reading		.01			-.06
Short-term memory		.14 [†]			.10
Attention control		.04			.04
Speed of processing		-.10			-.06
Visual-spatial skills		.15*			.13 [†]
Vocabulary		.17*			.17*
R ²	.11***	.20***		.15***	.23***
ΔR^2		.09**			.08***

Note. * $p < .05$; ** $p < .01$; *** $p < .001$; $† p = .054$; $† p = .06$

Table 3.6*Predicting sums in story context with emergent writing and orthographic knowledge*

Variable	Model 1 (β -values)	Model 2 (β -values)	Variable	Model 1 (β -values)	Model 2 (β -values)
Emergent writing	.27***	.09	Orthographic knowledge	.23**	.07
Shared storybook reading		.01			.01
Short-term memory		.13 [†]			.13 [†]
Attention control		.06			.09
Speed of processing		-.08	Not included ^a		
Visual-spatial skills		.11			.15*
Vocabulary		.20**			.20**
R ²	.07***	.16***		.05**	.18***
ΔR^2		.09***			.13***

Note. * $p < .05$; ** $p < .01$; *** $p < .001$; $† p = .06$; a. did not correlate with orthographic knowledge.

Discussion

Similar to previous research, the present study shows that early literacy skills co-vary with early math development (e.g., De Smedt et al., 2010; Krajewski & Schneider, 2009; Purpura et al., 2011). Correlations in the current study were low to moderate ranging from .18 for non-symbolic sums and orthographic knowledge to .39 for sums in story context and letter knowledge. After taking effects of all control variables into account some correlations between literacy and numeracy remained significant, which indicates that similar cognitive processes are active or that other not measured skills might explain overlap. Letter knowledge remained a significant predictor of sums in story context and rhyming of non-symbolic sums, explaining 6.25 % and 4.84 % of the variance, respectively (Alloway et al., 2005; DeSmedt, Taylor, Archibald, & Ansari, 2010; Piasta et al., 2010; Simmons et al., 2008). Both literacy and numeracy skills may share ease of manipulating verbal codes as can be derived from the study by Dehaene et al. (2003) showing brain activity in the same cortical regions. In so far overlap can be explained as the result of the in the current study measured cognitive and language factors, visual-spatial skills explained most co-variance. These skills partly or completely explain the co-variance between solving sums and familiarity with written forms as appears from the results of the regression analyses. At a young age when letters and word forms are not yet stored in long-term memory, children may heavily rely on visual-spatial representations when holding characteristics of written forms in mind for a short period (Bull et al., 2008), and words are mainly distinguished by means of their visual shape (Levy et al., 2006). Moreover, visual-spatial skills play an important role early in math development. The inborn ability to immediately see amounts up to four without counting (subitizing) may for instance be associated with cerebral circuits of our visual-system (Dehaene, 2011). When deciding whether two digits are the same (i.e., 4 and 5) processing the visual shape as well as linking numbers to quantities is essential (Dehaene, 2011). When linking numbers to quantities, visual-spatial skills enable a visual mental representation of numbers, which helps by deciding what is more (i.e., 4 or 5) (Krajewski & Schneider, 2009). It seems plausible that letters and numbers can more easily be distinguished and remembered by means of their shape, when visual-spatial skills are better developed (Shatil, Share, & Levin, 2000). Moreover, the weak relationship between rhyming and visual-spatial skills seems a plausible finding, because rhyming appeals less than

emergent writing, orthographic and letter knowledge to the ability to recognize written forms.

Only when predicting sums in story context, vocabulary in addition to visual-spatial skills explains co-variance among literacy and numeracy (cf. Purpura et al., 2011; Seethaler et al., 2012). Extracting relevant numerical information from a story appeals to children's vocabulary (Fuchs et al., 2006). Vocabulary did not explain co-variance in the non-symbolic condition as these sums appeal to a lesser extent to verbal abilities than do sums in a story context (Simmons & Singleton, 2008).

Pre-schoolers often face novel tasks that strongly appeal to short-term memory capacities (Alloway et al., 2005; Bull et al., 2008) which may explain why short-term memory also explains some co-variance albeit only when sums are presented in story context. Effects were only marginally significant. The differential effect of short-term memory on non-symbolic sums versus sums in the story context may be due to differences in memory load among the two simple sum conditions (Rasmussen & Bisanz, 2005). In the story context, the children had to remember the story, whereas in the non-symbolic condition, children had the opportunity to use the checkers simultaneously with the experimenter, which may reduce memory load.

Finally, phonological awareness is in general stronger related to symbolic than to non-symbolic numeracy skills, probably because symbolic math skills rely more on verbal codes than do non-symbolic math skills (e.g., Dehaene et al., 2003; Geary et al., 2012; Simmons & Singleton, 2008). Surprisingly we found comparable correlations between rhyming and sums in the non-symbolic ($r = .32$) versus the story context condition ($r = .34$). The sums in both contexts had to be read aloud because of the young age of the children in the current study (4; 3–4; 9 years). Consequently both conditions contained anyhow a verbal component, which may explain comparable effects of rhyming in both conditions.

Although speed of processing, attention control, and shared storybook reading were all significantly correlated with all literacy and numeracy measures, these variables did not explain the variance shared by early literacy and numeracy. Although correlations with the other mediators were low to moderate, there was no evidence for multicollinearity as an explanation for these null-results. Shared book reading may not explain co-variance as it had rather specific effects on literacy development, as appeared from the marginally to low correlations

with the sums compared to the much stronger correlations with the literacy skills. Attention control may be less influential than is short-term memory, when predicting early numeracy from several EF skills (Kroesbergen et al., 2009), and may gain impact later on when instruction becomes more formal. Unlike Furnes & Samuelsson (2011) and Cirino (2011), we found rather low correlations between speed of processing and early numeracy and literacy. Probably later on in math and reading development when skills become automatized, speed of processing becomes more important (Geary, 2011) and a source of covariation. An alternative hypothesis is that although a slow processing speed may be associated with delays in academic skills, it may not be a precursor of developmental delays in numeracy and literacy (Weiler et al., 2003).

Conclusions

The commonly reported substantial co-variance among early literacy and early numeracy skills (Krajewski & Schneider, 2009) differs depending on the literacy skill and the numeracy skills measured. Of the literacy skills assessed, rhyming and letter knowledge correlated strongest with both types of sums. The common variance among early literacy, especially rhyming and letter knowledge, and sums can be partially explained by visual-spatial skills, short-term memory, and vocabulary. More specifically, significant effects of familiarity with the written form on sums became non-significant after taking visual-spatial skills into account. When sums were presented as stories, vocabulary and short-term memory (although only marginally) also reduced the common variance. Shared storybook reading and speed of processing did not explain any unique co-variance. To make understandable the more puzzling finding that attention control did not explain co-variance we hypothesize that the ability to stay attentive grows in importance when formal instruction has begun and time for learning new skills is limited.

Within the school curriculum it seems important that teachers are aware of the fact that delays in literacy often go together with delays in mathematics and vice versa. As certain early literacy and early numeracy skills co-vary, it is vital to test early numeracy skills when delays in early literacy are noticed and vice versa, early literacy skills should be monitored when delays in early numeracy are diagnosed. Moreover, interventions to enhance early literacy and numeracy skills should take into account that, as a result of the importance of domain-

general skills, training of early numeracy may support early literacy skills and, vice versa, training of early literacy may support early numeracy.

Limitations and Future Directions

Although phoneme deletion/detection might be a more sophisticated measure of phonological awareness, in the current study we used rhyming as indicator of phonological awareness because the phoneme detection task we applied appeared to show bottom effects for the 4-year olds in the current sample.

Because all skills were assessed at the same time-point we cannot make inferences about causal relationships; domain-general skills may explain variance among certain early numeracy and literacy skills, but when numeracy and literacy skills develop this might also affect the development of domain-general skills.

In the current study we found specific relations among rhyming, letter knowledge and sums. Relations among early literacy and other early numeracy skills like counting and estimation skills, and comparing amounts, can be assessed in future research in order to make more general assumptions regarding the co-variance among early numeracy and early literacy. Moreover, other general cognitive abilities can be assessed in order to expand current outcomes.

Intervention studies testing whether training of general skills also enhances numeracy and literacy skills, or whether training numeracy skills affects literacy development and vice versa, may lead to deeper insights in the co-variance among early numeracy and literacy skills.

Chapter 4

Causal relations among executive functions and academic skills from preschool to end of first grade

Abstract

In a sample of 87 children we tested whether changes in executive functions (EF) from preschool to end of first grade are causally related to changes in numeracy and literacy skills. First a regression analysis testing effects of preschool EF (memory and inhibition) on academic outcomes in Grade 1 was applied. We controlled for variation attributable to school-level, several covariates, and preschool academic skills. For testing effects of changes, a fixed effects analysis was applied to a repeated measures design. The long-term findings indicated that early delays in EF are often temporary and no strong predictors of academic skills in Grade 1. Yet changes in EF were causally related to math, reading, and writing development. No differential effects of EF on math versus reading skills were found. Implications for the school curriculum and interventions are discussed.

Under review as:

Davidse, N. J., de Jong, M. T., & Bus, A. G. Causal relations among executive functions and academic skills from preschool to end of first grade.

Introduction

Executive functions (EF) are a commonly used umbrella term for a set of interrelated cognitive processes that are required in planning and problem solving (Diamond, 2013). Components of executive functions are 1) inhibition and attention control (i.e., staying focused for a period thereby ignoring distractors), 2) the ability of holding information in mind and manipulating information, referred to as short-term memory and working memory, and 3) cognitive flexibility, referring to the ability of changing perspectives and searching for new problem solutions if necessary (e.g., Blair, Zelazo, & Greenberg, 2005; Davidson, Amso, Anderson, & Diamond, 2006; Diamond & Lee, 2011; Diamond 2013). Early EF skills may cause delays in early numeracy and literacy (e.g., Davidse, de Jong, Bus, Huijbregts, & Swaab, 2011; Duncan et al., 2007; Kegel, van der Kooy-Hofland, & Bus, 2009; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; McClelland et al., 2007; NICHD, 2003; Welsh, Nix, Blair, Bierman, & Nelson, 2010), and predict later math and literacy development (Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008), even when controlling for earlier academic skills (Duncan et al., 2007). For instance, when children are easily distracted they miss essential information provided in kindergarten and first grade, as a result of which children lag behind in alphabetic skills after being three months in first grade (Kegel & Bus, 2013).

Most studies on effects of EF on numeracy and literacy development focus on preschool and kindergarten, with time spans ranging from half a year to two years (e.g., Blair & Razza, 2007; Clark, Pritchard, & Woodward, 2010; Foy & Mann, 2013; McClelland et al., 2007; Welsh et al., 2010), on effects on math and reading development from Grade 1 and up (e.g., Altemeier, Abbott, & Berninger, 2008; Mazzocco & Kover, 2007; Monette, Bigras, & Guay, 2011; Toll, Van der Ven, Kroesbergen, & Van Luit 2011), or solely on one particular point in time (e.g., Davidse et al., 2011; Espy et al., 2004; Kroesbergen et al., 2009). Especially longitudinal studies are vital to argue that preschool EF skills are causally related to later academic outcomes (Raghubar, Barnes, & Hecht, 2010). In so far studies relate early EF skills to later academic skills (commonly measured later in preschool or in kindergarten) (e.g., Blair & Razza, 2007; Clark et al., 2010; Foy & Mann, 2013), they do not control for early academic skills (Raghubar et al., 2010), or do not take into account possible effects of covariates. In fact, positive relations among early EF skills and later academic skills might be spurious due

to potentially relevant covariates causing spurious outcomes (Willoughby, Kupersmidt, & Voeger-Lee, 2012). Potential covariates are variables such as educational level of the parents that may relate to counting and reading activities at home in preschool age (e.g., Davidse et al., 2011; LeFevre et al., 2009) but simultaneously to the development of EF (NICHD, 2003).

Apart from the lack of longitudinal studies on EF and academic outcomes that take into account effects of early academic skills and other covariates, studies do not take into account that EF rapidly develops during early childhood. Attention is rather stable but still variable until the age of 6-8 (Posner & Rothbart, 2000), and inhibition, switching, and memory skills are developing well into adulthood (Davidson et al., 2006; Diamond, 2013; Gathercole, Pickering, Ambridge, & Wearing, 2004). Changes in EF may therefore be a more reliable indicator than measurements at one particular point in time. Although commonly the conclusion is drawn that children entering preschool with low EF and/or emergent academic skills are at risk for experiencing difficulties learning to read, write, and solve sums, these children's EF skills might improve during kindergarten, resulting in less difficulties with learning to read, write, and solve sums throughout kindergarten and in Grade 1. In other words, even when preschool EF does not relate to math, reading, and writing in Grade 1, we might find relations when we take into account that EF skills may be rapidly changing. By focusing on changes in EF and academic skills, we exclude the possibility that erroneously the conclusion is drawn that EF and academic skills are not causally related, whereas in fact changes in EF are related to academic outcomes. Over a short period (time span between pre- and posttest was on average 4.4 months) Willoughby et al., 2012 demonstrated for a sample of children aged 3.1 to 5.8 that relations among EF skills and academic skills were spurious due to confounder variables affecting both academic skills and EF. A replication in our lab in an older group of children (mean age 61; 3 months at pretest), with a one year time span (Kegel & Bus, in press), and other EF tests, revealed however that relations among EF and literacy development were not due to confounder variables, implying a causal relation between EF and literacy development.

A longer time-span may result in a greater variability in change and therefore may provide a stronger test of the effect of EF development on academic development (Willoughby et al., 2012). However, so far we know there are no studies predicting academic growth from preschool to first grade, from changes in EF over the same period. We therefore extended the prior research by looking

at long-term effects of EF development on numeracy and literacy development over two-and-half years, from preschool (when children were on average 55 months old) to end of first grade (when children were on average 83 months old). We controlled for potential confounder variables including early academic skills, which are moderate to strong predictors of later academic achievement (Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Muter et al., 2004; Raghubar et al., 2010; Whitehurst & Lonigan, 1998). We included two core EF skills, memory and inhibition, that both start developing earlier than cognitive flexibility (Diamond, 2013).

The first main goal was testing whether preschool EF (short-term memory and inhibition) is related to math, reading, and writing skills in preschool and subsequently in Grade 1, when controlling for possible confounder variables, and in the long-term tests also for preschool numeracy and literacy skills. For this purpose we executed regression analyses predicting academic skills in preschool and first grade, thereby controlling for variation attributable to school and confounder variables.

The second main goal was testing whether over a three year time-span changes in EF are related to changes in academic development. For this purpose, we applied a Fixed Effects Analysis (FEA) to a repeated measures design (Twisk, 2006; Willoughby et al., 2012). We hypothesized that a relation between EF development and numeracy and literacy development may exist, even when there is no direct relation between preschool EF and academic achievement in Grade 1. EF may be low at the start of preschool but improve during preschool and first grade thereby no longer being a predictor of growth in reading and math (Bodrova & Leong, 2007; Burrage et al., 2008). Numeracy and literacy development are both included because previous findings suggest that effects of EF on numeracy development are stronger compared to effects on literacy development (Blair & Razza, 2007; Duncan et al., 2007; McClelland et al., 2007).

In a repeated measures design it would be best to apply exactly the same emergent academic and EF tests at the first and second assessment. Unfortunately it is impossible to apply the same tests in Grade 1 as in preschool, because early skills need to be measured within a critical period to avoid non-normal distributions due to bottom and ceiling effects (Paris, 2005; Paris & Luo, 2010). Using the same tests in preschool and Grade 1 would lead to ceiling effects in Grade 1 (Paris, 2005; Paris & Luo, 2010), and, vice versa, testing Grade 1

skills in preschool would result in bottom effects. The best indicator of working memory, a digit span backwards task, for instance appeared to be too difficult for 4 year-olds in our study and previous ones (Bull et al., 2008). In preschool we therefore applied the digit span forward task, measuring short-term memory which is considered to be a precursor of working memory (Diamond, 2013). In preschool we assessed in addition to short-term memory and inhibition, two early literacy skills (phonological awareness with a rhyming task and emergent writing with a writing task) and several early numeracy skills that in previous research were moderate to strong predictors of conventional math, reading, and writing skills (Jordan et al., 2006; Muter et al., 2004; Whitehurst & Lonigan, 1998). As Grade 1 math variable, we had sums and as literacy measures dictation and word reading. To be able to compare scores on pre- and posttest, all tests scores were standardized.

Method

Participants

Participants were 87 children with a native Dutch background. The sample was recruited from 7 randomly selected schools in a province in the Western part of the Netherlands. The schools were attended by Dutch-speaking children from low- to middle class families. The study was carried out after informed parental consent was received. For the first time of testing, children who just started in preschool were selected (age range 52 to 58 months; mean age was 54.52 months; $SD = 1.95$ months). These children were tested again slightly more than two years later at the end of Grade 1. Mean age at the second time of testing was 82.75 months ($SD = 2.90$ months; range 72 to 89 months). In preschool, four of the 87 children refused to participate, resulting in 83 participants (38 boys and 45 girls) who completed the measurements at both times.

Educational Level of the Mother

Mothers reported their highest level of education on a seven-point-scale ranging from primary education to university degree.

Preschool Numeracy Skills

Counting principles. This task, adapted from Geary, Hoard, and Hamson (1999), assessed children's ability to detect violations of the counting principles: One-to-one correspondence, order irrelevance and abstraction. The child was

first introduced to a puppet that was just learning how to count and needed assistance. White and black checkers were used for counting. In part of the trials, the total amount counted by the puppet was incorrect. After each trial the experimenter therefore asked: "Did he count correctly? Show how you would count the stones." This task consisted of a total of eight items to assess the child's understanding of one-to-one correspondence ($n = 4$), order irrelevance ($n = 2$), meaning that you can count not only from left to right, but also in random order, and abstract from features like color ($n = 2$). Based on the child's answers: 1) whether the puppet counted correct, and 2) whether the number of checkers counted by the child equaled the number of checkers the puppet had to count, it was scored whether the child was familiar with the counting principle assessed (max score was 8). Percentage correct was calculated.

Number knowledge and magnitude comparison. In the number knowledge task adapted from Griffin (2002), children were asked: "Which number precedes five?", and "which number comes after seven?" We also assessed magnitude comparison by asking: "I will say two numbers, you may tell me which one is bigger: nine, two.", or by asking: "Which number is smaller: Four, three?" This task consisted of a total of four items. Percentage correct was calculated.

Conservation principles. We assessed whether children understood that the total number of a set remains the same after rearranging the items without changing the number. The experimenter counted a row of checkers (rows of four, six, eight and nine checkers, respectively) and then split the row into two parts and asked the child: "How many stones are here together" (circling her finger around all the checkers). The same was done the opposite way (rows with five, seven, eight and nine checkers respectively). In all, this task consisted of eight items. Percentage correct was calculated.

Estimation. In this task adapted from Jordan and colleagues (2006), children were shown five cards with 3, 8, 15, 25, or 35 dots placed haphazardly on each card. The cards were presented to the child in the above order so that the number of dots increased each time they were shown a new card. The experimenter showed each card and said: "About how many dots do you see?", next the card was turned. The child received the score of 1 if he or she estimated within 25% of the actual number of dots on the card. The maximum number of points was five. Percentage correct was calculated.

Number naming. On a computer screen, children were shown numbers from 0 to 20, one at a time, in the following order: 1, 13, 4, 17, 2, 11, 8, 14, 20,

5, 16, 3, 12, 6, 0, 19, 7, 15, 9, 18, and 10. After 4 seconds, the next number was automatically presented. Children were instructed to name the numbers as soon as possible. Percentage correct was calculated.

Nonsymbolic and symbolic addition and subtraction sums. This task was adapted from Jordan and colleagues (2006). In the nonsymbolic condition, children were able to use material (checkers) to solve the sums. The experimenter said for example: “Look, I have two stones. Now I’m covering them. Look carefully, I’m adding one stone. How many stones do I have now? Show it to me by using your stones and then tell me the number.” The addition as well as the subtraction sums had one practice item where the experimenter corrected the child if needed. A total of four addition (2+1; 4+3; 2+4; 3+2) and four subtraction sums (3-1; 7-3; 5-2; 6-4) were used. In the symbolic condition, exactly the same sums were presented, but this time in a story context. Children were not allowed to use the checkers to solve the sums. The experimenter asked for example: “Mary has six bananas, Joe takes away four bananas. How many bananas does Mary have now?” For both tasks percentage correct was calculated.

Composite measure. A composite measure of the scores on all the early numeracy subtests was calculated by adding scores on the early numeracy subtests in percentages and dividing the total score by the number of subtests (e.g., Jordan, Kaplan, Locuniak, & Ramineni, 2007). This resulted in a mean correct score on early numeracy in percentages. Alpha reliability over all subtests equaled .70.

Preschool Literacy Skills

Emergent writing. Children were asked to write down their proper name and the words *mama* [mum], *vuur* [fire], *kaas* [cheese], *wiel* [wheel], and *boot* [boat]. The writings were scored based on a scale ranging from 0 (scribble produced by scratching) to 13 (conventional spelling); see Levin & Bus (2003) for a detailed description. The writing scores were summed, resulting in a total score on emergent writing (max score is 78). Inter-coder agreement ranged from .80 (cheese) to .91 (wheel). Any disagreement was resolved through discussion. Alpha reliability equaled .91.

Rhyming. On a computer screen one picture appeared (for example a picture of a hand), and simultaneously the question: “Which word rhymes with *hand* [Dutch word for hand]?” is read aloud by the computer. Next three pictures appeared in succession and simultaneously the name of the object was read

aloud (for example, *kast* [cupboard], *mand* [basket], *vaas* [vase]). The child’s task was to name or point to the rhyming word (in this example *mand* [basket]). One practice trial and 10 test trials were presented. The score equaled the number of correct responses (max score is 10). Alpha reliability equaled .83.

Preschool Executive Functions

Short-term memory. The ‘Digit span forward task’ of the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983) was used as indicator of short-term memory. In this task, the child repeated numbers in exactly the same order. The test started with one practice item of two numbers similar to the first level and increased with one number every next level (three items per level). The test was discontinued if a child made an error in two consecutive items of the same length. The score equaled the number of correct responses.

Inhibition. Peg tapping (Diamond & Taylor, 1996) was included as indicator of inhibition. When the experimenter tapped once, the child had to tap twice and vice versa, thereby inhibiting his or her natural response to mimic the experimenter’s behavior. The task consisted of 16 items. Alpha reliability equaled .85. The total score equaled the number of correct responses.

Math Skills in Grade 1

Math skills in Grade 1 were tested using a standardized test for mental arithmetic, *DLE-Test Hoofdrekenen*, [DLE-Test Mental Arithmetic] (De Vos, 2001). Children receive a two-sided form with a total of 200 addition, subtraction, multiply, and division sums of increasing difficulty up to 100. The test starts with sums up to 10. Within 3 minutes, children need to solve as many sums as possible whereby skipping sums is not allowed. The score is the total of correct sums minus the incorrect ones. Alpha reliability reported in the manual is .96 (De Vos, 2001).

Literacy Skills in Grade 1

Dictation. Children were asked to write down 7 Dutch words: *Spiegel* [mirror], *gezicht* [face], *schommel* [swing], *inktvis* [inkfish], *knecht* [farm-hand], *dolfijn* [dolphin], and *borstel* [brush]. These words were chosen, because of the variety in sounds. A correct spelled word equaled 3 points. For every error, one point was subtracted. The maximum score equaled 21. Alpha reliability equaled .95.

Word reading. The standardized word reading test, 'Eén-Minuut-Test' [one minute test], was administered to assess word reading skills (Brus & Voeten, 1973). Within one minute, words have to be read aloud from a list containing 116 words. The score equaled the number of correct responses minus the incorrect ones.

Executive Functions in Grade 1

Working memory. The subtest digit span backwards of the WISC-III (Wechsler, 1992) was administered for assessing working memory. The test starts with repeating two digits and in every level the number of digits increases with one. The total score equals the number of correct responses (max. 14).

Inhibition/switching. The Dimension Change Card Sort Task (Zelazo, 2006) was used as indicator of inhibition and switching abilities. Cards contained a red truck, a blue truck, a red star or a blue star. In the first part, children had to sort the cards by color, in the second part by figure (half of the children started with the 'figure-condition'). The test condition consisted of 12 cards, either with or without a black border. Children were instructed to play the color game when a card contained a border and the figure game when cards had no border. When showing a card, the experimenter only mentioned whether the card was with or without a border. The score equaled the number of correct responses in the test condition. For a detailed description see Zelazo (2006). We had missing data on this test for 30 children, because some experimenters had made mistakes in applying the test. Alpha reliability equaled .73.

Procedure

Parents received a flyer with information about the purpose of the study and the procedure (number of sessions, activities during the sessions, etc.). The phone number and e-mail address of the first author were provided in the pamphlet in case parents wished additional information. Parents signed a written consent for participation.

All measures were individually administered in a spare room at school by the main researcher or one of seventeen trained bachelor and master students. The preschool tests were spread over six sessions. Session order was counterbalanced between participants whereas the order of tasks within a session was fixed. At the end of Grade 1 testing took place in one session lasting about 40 minutes. To verify the quality of testing and data coding all sessions were videotaped by

a digital camera in a fixed position. Due to technical problems, the score on the number naming task of one child is missing as well as four children's score on *Mental Arithmetic*. Therefore N varies somewhat across analyses.

Data analysis

In the first two sets of analyses, we used Huber-White estimates to correct for clustering of measures, because the subjects were recruited from a limited number of schools ($N=6$). Thus the nonindependence of observations within schools was accommodated for. The estimates were included in the Complex Sample General Linear Model (CSGLM, SPSS 19). In the first analysis, preschool academic skills (number sense, rhyming, or emergent writing) was the dependent variable, and age, gender, educational level of the mother and preschool EF (short-term memory or inhibition) were the covariates. In the second set of analyses, Grade 1 academic skills (math, reading, or writing) was the dependent variable, and age, gender, educational level of the mother, preschool EF (short-term memory or inhibition), and the corresponding preschool academic skill (number sense, rhyming, or emergent writing) were the covariates.

Next a Fixed Effect Analysis (FEA) was carried out regressing changes in academic achievement on changes in EF. The first model regressed pretest academic achievement on pretest EF and demographic covariates. The second model regressed posttest academic achievement on pretest EF, demographic covariates, and pretest academic achievement. The third model used the availability of longitudinal (repeated measures) data to remove all of the measured and unmeasured *time invariant* characteristics that may confound the association between EF and academic functioning. The FEA model takes into account that observations are clustered within children by including a random intercept:

$$\text{Academic skills}_{ij} = \beta_{0ij} + \beta_1 (\text{executive functions}_{ij})$$

$$\beta_{0ij} = \gamma_{00} + u_{0j} + e_{0ij}$$

$$\gamma_{00} = \text{average intercept}$$

$$u_{0j} = \text{unexplained deviation from average intercept } \gamma_{00} \text{ for child } j$$

$$e_{0ij} = \text{residual error}$$

The slope may vary as well between children and should be allowed to be random, implying that instead of a fixed effect for EF (β_1, EF_{ij}) we have to add an interaction between EF and child to the model (β_{1j}, EF_{ij}). As a next step, intercept and/or slope were allowed to differ between schools as well. Likelihood ratio

Table 4.1
Descriptive statistics and correlations among variables

Test (N = 83)	Mean (SD)	Inhibition preschool	Number sense preschool	Rhyming preschool	Emergent writing preschool	Working memory Grade 1	Inhibition Grade 1 (N = 53)	Mathematics Grade 1	Reading Grade 1	Dictation Grade 1
Short-term memory pre-school	6.76 (1.81)	.09	.28*	.36*	.20 (p = .07)	.08	.24	-.04	.13	.20
Inhibition preschool	13.15 (2.95)	-	.37**	.37**	.29*	.08	.17	.35*	.15	.25 (p = .07)
Number sense preschool (percentage correct)	43.33 (10.10)		-	.53**	.42*	.17	.22	.40**	.29**	.34**
Rhyming preschool	7.42 (2.73)			-	.34**	.23*	.21	.21 (p = .06)	.34**	.35**
Emergent writing preschool	46.61 (12.54)				-	.07	.16	.35**	.35**	.45**
Working memory Grade 1	3.61 (1.06)					-	.24	.28*	.26*	.27*
Inhibition Grade 1 (N = 53)	8.50 (2.59)						-	.16	.24 (p = .09)	.25 (p = .08)
Mathematics Grade 1	17.86 (6.56)							-	.49**	.48**
Reading Grade 1	30.12 (15.08)								-	.63**
Dictation Grade 1	16.29 (2.64)									-

tests were applied to evaluate whether or not random intercepts for school or random slopes for individuals and school should be considered. Results for the most optimal models are presented in Tables 4.2 and 4.3.

In order to establish a common metric for interpreting all of the results, achievement and EF measures were standardized. Hence, unstandardized regression coefficients for EF measures represent the amount of change in achievement (in standard deviation units) that result from a hypothesized one standard deviation unit change in EF.

Results

Correlations and Descriptive Statistics

In Table 4.1 descriptive statistics and correlations among variables are displayed. Preschool EF skills were significantly related to the preschool academic skills numbers sense, rhyming, and emergent writing. With the exception of the significant correlation between preschool inhibition and Grade 1 mathematics, preschool EF skills did not correlate with academic skills in Grade 1. The preschool academic skills did correlate significantly with academic skills in Grade 1. Due to the great variability early in EF development, preschool EF skills did not correlate with EF skills in Grade 1. All preschool academic skills correlated moderately, likewise all academic skills in Grade 1 correlated moderate to strong.

Memory. As can be extracted from outcomes at pretest (see Table 4.2), short-term memory in preschool was significantly related to the overall measure of number sense ($B = .32$; $p < .05$) and to rhyming ($B = .27$; $p < .05$). Emergent writing however revealed a different pattern: Preschool short-term memory was not related to preschool emergent writing.

Outcomes at posttest in Grade 1 showed a decrease in the association between short-term memory and academic skills. After controlling for preschool numeracy skills ($B = .45$; $p < .001$), preschool short-term memory was not significantly related to sums. Likewise, preschool short-term memory was not related to reading and writing in Grade 1 when controlling for a marginal effect of preschool rhyming ($B = .40$; $p = .08$) and a significant effect of emergent writing ($B = .19$; $p < .05$).

However, applying a Fixed Effects model (differences) revealed significant effects of EF on academic skills. Changes in memory development between preschool and end of first grade were significantly related to changes in math

Table 4.2
Regression coefficients relating math, reading, and writing development to memory development

	Number Sense Preschool - Sums Grade 1			Rhyming Preschool - Word Reading Grade 1			Emergent writing Preschool - Dictation Grade 1		
	Pretest	Posttest	Difference	Pretest	Posttest	Difference	Pretest	Posttest	Difference
	number sense B (SE)	sums B (SE)	ence B (SE)	rhyming B (SE)	word reading B (SE)	B (SE)	emergent writing B (SE)	dictation B (SE)	B (SE)
Age	.05 (.06)	.03 (.05)		.13 (.06)	-.03 (.07)		.06 (.04)	-.03 (.02)	
Gender	-.33 (.23)	-.05 (.21)		.35 (.22)	-.02 (.18)		.28 (.26)	.06 (.06)	
Education mother ^a	.03 (.05)	.10 (.08)		.15* (.05)	.00 (.03)		.14* (.06)	.05 (.04)	
EF (memory) ^b	.32* (.11)	-.21 (.11)	.27** (.07)	.27* (.12)	-.01 (.06)	.26*** (.07)	.11 (.08)	.04 (.04)	.15* (.06)
Pretest academic skills		.45** (.11)			.40+ (.21)			.19* (.08)	

Notes. ^a Education = highest educational level mother (ranging from 1 to 7). ^b Using pretest score (short-term memory) as predictor of pretest and posttest literacy outcomes but using memory development (short-term memory preschool – working memory Grade 1) when predicting difference in literacy outcomes. * $p < .05$; ** $p < .01$; *** $p < .001$; + $p = .08$

over the same period ($B = .27$; $p < .01$), and likewise to changes in reading ($B = .26$; $p < .001$) and in writing ($B = .15$; $p < .05$).

According to the log-likelihood tests, in none of the models relating memory to academic development did a random slope result in model fit improvement. Therefore, a random slope was not included. School as random intercept or slope in addition to subject did not improve the models relating memory development to academic development and was therefore not included as a random factor. Outcomes for the models with the best fit are presented in Table 2.

Inhibition. At pretest, inhibition was significantly related to number sense controlling for background variables but it was not significantly related to emergent writing and rhyming (see Table 4.3).

At posttest, inhibition did not predict academic outcomes in Grade 1 after controlling for background variables and significant effects of preschool numeracy skills ($B = .41$; $p < .01$), preschool rhyming ($B = .37$; $p < .05$), and a marginally significant effect of emergent writing ($B = .24$; $p = .06$).

However, in all cases did differences in inhibition development relate to differences in academic development: For math development the effect approached significance ($B = .16$; $p = .07$), and for reading and writing effects were significant ($B = .27$; $p < .01$ and $B = .17$; $p < .05$). According to the log-likelihood tests, in none of the models relating inhibition to academic development did a random slope result in model fit improvement of the models. School as random intercept in addition to subject improved the model relating inhibition to reading development. Outcomes for the models with the best fit are presented in Table 4.3.

Discussion

The current study aimed at testing causal relations between EF skills and academic skills. To this end we tested: 1) whether EF skills in preschool relate to academic skills in Grade 1 when controlling for preschool academic skills and other possible covariates, and 2) whether changes in EF are causally related to changes in academic development from preschool to end of first grade. We found that after controlling for several covariates, EF behavior at the start of preschool is mostly predictive for academic skills at the same time but early delays in EF (memory and inhibition) are no longer a significant predictor of math and literacy outcomes in Grade 1. When however changes in EF are taken

Table 4.3

Regression coefficients relating math, reading, and writing development to inhibition development

	Number Sense Preschool – Sums Grade 1			Rhyming Preschool – Word Reading Grade 1			Emergent writing Preschool – Dictation Grade 1		
	Pretest	Posttest	Difference	Pretest	Posttest	Difference	Pretest	Posttest	Difference
	number sense B (SE)	sums B (SE)	ence B (SE)	rhyming B (SE)	word reading B (SE)	B (SE)	emergent writing B (SE)	dictation B (SE)	B (SE)
Age	-.01 (.06)	-.10 (.05)		.08 (.04)	-.05 (.08)		.05 (.05)	-.05 (.02)	
Gender	-.49 (.25)	.14 (.21)		.46 (.35)	.03 (.26)		.55 (.26)	.07 (.10)	
Education mother ^a	.06 (.06)	.01 (.05)		.16* (.06)	.02 (.04)		.12 (.06)	.04 (.04)	
EF (inhibition) ^b	.38* (.13)	.22 (.10)	.16 ⁺¹ (.08)	.19 (.16)	.03 (.11)	.27** (.09)	.16 (.11)	.05 (.06)	.17* (.07)
Pretest academic skills		.41** (.10)			.37* (.12)			.24 ⁺² (.12)	

Notes. ^aEducation = highest educational level mother (ranging from 1 to 7). ^bUsing pretest score (inhibition) as predictor of pretest and posttest literacy outcomes but using inhibition development (inhibition preschool – inhibition/switching Grade 1) when predicting difference in literacy outcomes. * $p < .05$; ** $p < .01$; *** $p < .001$; ⁺¹ $p = .07$; ⁺² $p = .06$

into account, EF is a moderately strong predictor of Grade 1 math, reading, and writing performance. These results indicate that EF as assessed in preschool is not a stable feature but very variable. Results thus support our hypothesis that it is important to take into account that EF's at this young age are variable. Consequently, there are no direct effects of preschool EF on reading, writing, and math skills in Grade 1. This implies that existing executive function measures are not usable as predictors of children's academic development. Young children entering preschool with delays in early EF and, because of that, in academic skills, are able to catch up in EF due to maturation, home and school influences, and to develop math, reading, and writing skills.

Our findings are in line with the theory that executive functions explain differences in academic development. Contrary to Willoughby's conclusion (Willoughby et al., 2012) that the relationship between EF and academic development is spurious due to time invariant confounder variables, our results make a strong argument for a causal relation between EF and academic skills. All relations between changes in EF and academic skills were positive, indicating that when children's EF skills improve, their academic skills grow as well and simultaneously that when EF skills get worse, academic skills might not improve. Even though this is no experimental evidence it makes a strong case for the theory that learning partly depends on EF.

More specifically we found that 1 *SD* change in memory development led to about 1/3 *SD* change in math development and reading development, and about 1/6 *SD* change in writing development. Effects of inhibition development on math development were smaller compared to the effects of memory: 1 *SD* change in inhibition development led to about 1/6 *SD* change in math development. Effects of inhibition on reading and writing development were comparable with the effects of memory development (1 *SD* change in inhibition led to about 1/3 *SD* change in reading and 1/6 *SD* in writing development).

For all academic outcomes, both working memory and inhibition are important. For math however, memory development was a stronger predictor than was inhibition. In all it implies that being able to maintain and manipulate information in memory and ignoring distracters are essential skills for early reading and math (Diamond & Lee, 2011). We did not find support for the hypothesis that EF has a stronger effect on math compared to literacy development (Blair & Razza, 2007; Duncan et al., 2007; McClelland et al., 2007). Our time-span was larger compared to previous studies: almost three years compared to at most

two years in prior studies. Because emergent academic and EF skills both rapidly develop during early childhood (e.g., Davidson et al., 2006; Dehaene, 2011; Paris, 2005), a longer time-span may result in greater variability in change and therefore provide a stronger test of the effect of EF development on academic development (Willoughby et al., 2012).

The finding that number sense and rhyming are substantial predictors for mathematics and reading respectively, gives enough reason to control for these early academic skills when predicting academic outcomes from other factors such as EF, which is not common practice (Raghubar et al., 2010). This finding also highlights the importance of these early academic skills for formal reading and math instruction in Grade 1 (Jordan et al., 2006; Muter et al., 2004; Whitehurst & Lonigan, 1998). Moreover, all academic skills correlated moderate to strong, indicating that development in mathematics tends to go together with development in reading (Davidse, de Jong, & Bus, 2013). Compared to rhyming and number sense, emergent writing was a less strong predictor of writing in Grade 1. Probably behavior assessed by the lower scores of the writing scale does not have much in common with the higher scores, whereby the lower levels are not predictors for the higher ones; scores range from figures through scribbles and random letter strings to phonetic writing (Both-de Vries, 2006; Levin & Bus, 2003).

The current findings may imply that next to home influences (e.g., NICHD, 2003), the school curriculum may affect children's EF skills. Research among teachers in the United States indeed has indicated that teachers nowadays are more aware of the importance of EF skills for academic development and a majority mentions that they practice EF skills directly although intensity may differ (Morgan-Borkowsky, 2012). It remains however important that teachers are aware of children who do not catch up their EF skills during preschool and kindergarten, and as a result may not sufficiently develop their early academic skills. For these children additional training of EF skills might be useful and should be included in early intervention programs aimed at improving early numeracy (e.g., Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Siegler & Ramani, 2009) or early literacy skills (e.g., Bodrova & Leong, 2007). Previous research demonstrated that already in 4-5 years olds, EF skills can improve by means of training (Diamond & Lee, 2011).

In sum, the current study offers strong evidence for the hypothesis that memory and inhibition are causally related to math, reading, and writing

development in kindergarten and Grade 1: Change in EF was significantly and positively related to change in all academic outcomes, whereas EF at the start of preschool did not predict Grade 1 achievement because EF is not a stable feature but changing over time. Children with delays in EF may thus be able to catch up their EF skills during preschool and kindergarten, resulting in better performance on math, reading, and writing later on. It seems therefore important that EF skills are monitored and stimulated in preschool and kindergarten. In some cases, additional training of EF skills could be beneficial and might prevent a downward spiral compared to children with more advanced EF skills. Yet, training of EF should not replace training of academic skills, as there is still a debate about the transfer effects of EF training to academic skills (Melby-Lervåg & Hulme, 2013). Our finding that preschool academic skills were moderate predictors of academic outcomes in Grade 1 after controlling for EF and other background variables indicates anyhow that it is vital to pay attention to academic skills in preschool and kindergarten.

Limitations

Inescapably the current study has limitations, most of which concern constraints in tests and design. Experimental manipulation, the gold standard of testing causal relations, requires that EF is trained apart from academic skills, and vice versa. Yet, EF skills are tied together with academic skills and it may not be possible to train both separately.

A for long-term research complicating factor is that tests for EF and academic skills are both age-dependent and not created to demonstrate shifts over time. They are primarily designed to make the developmental level in specific cognitive capabilities manifest. Based on the current data we can conclude that changes in EF have to be taken into account to predict academic development. However, because of different pre- and post tests, the theory based inference that academic skills in Grade 1 may improve because children may be able to catch up their EF skills during preschool and kindergarten, should be read with caution.

The assessment of EF by neuropsychological tests inevitably leads to assessment of cortical-subcortical circuitry common to many forms of EF and by implication, behavioral functioning (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008). To use them as measures to predict long-term development, may stretch their use beyond the purpose of their original design (Wasserman & Wasserman, 2012).

Finally, by means of FEA, stronger inferences about causality can be made, but estimates of the effects are more imprecise due to larger standard errors. Thus, although FEA reduces the risk of misleading interpretations of data, there always remains some uncertainty about the strength of the effect sizes.

Chapter 5

A twin-case study of developmental number sense impairment

Abstract

The current study reports on 9-year-old monozygotic twin girls who fail to make any progress in learning basic mathematics in primary education. We tested the hypothesis that the twins' core math problems were deficits in number sense that manifested as impairments in approximate and small number systems, resulting in impairment in non-symbolic as well as in symbolic processing. While age matched controls (eight typically developing girls) scored highly, the twins scored at chance on all number sense tasks. More specifically, on a non-symbolic comparison task, even in the simplest ratio condition of 1:2, and on a subitizing task including only numbers under 4, the twins performed at chance and significantly below the same age control group. Responsiveness to an intervention promoting number sense is discussed. As differences between verbal and performance IQ suggest, there seems to be a high degree of specificity in the twins' developmental number sense delays. The concomitant impairments for visual-spatial processing and working memory in the twins might explain the failure to develop number sense.

Published as:

Davidse, N. J., de Jong, M. T., Shaul, S., & Bus, A. G. (2014). A twin-case study of developmental number sense impairment. *Cognitive Neuropsychology*. doi: 10.1080/02643294.2013.876980

Introduction

This study examines the profiles of two 9-year-old monozygotic twins characterized by a failure to make any progress in learning basic mathematics in primary education. After a global assessment of the twins' general cognitive capacities and academic skills, we hypothesized that the twins suffered from a severe number sense deficit expressed in impairments in the approximation system as well as in the small number system, resulting in impairment in non-symbolic as well as in symbolic processing (Dehaene, 2011; Feigenson, Dehaene, & Spelke, 2004; Molko et al., 2003). Some consider those skills as core deficits in learning basic mathematics (Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Secondly, we hypothesized that their responsiveness to common interventions aimed at improving number sense skills would be low because they lacked skills that were at the basis of math development (e.g., Wilson et al., 2006). Particularly visual-spatial and/or working memory impairments may be seen as part of the root cause of the failure to develop number sense (Dehaene, 2011; Geary et al., 2009).

Delays in higher-level math skills (i.e., solving problems) despite normal achievement in other academic skills may be the result of deficits in elementary numerical processing (Price et al., 2007). According to recent insights, elementary numerical processing encompasses two numerical systems: A small number system with exact representations for numbers under four and an approximate number system (also called the Approximate Number System-ANS) which enables young children to approximately compare magnitudes (Dehaene, 2011; Feigenson et al., 2004; Molko et al., 2003). The numerical ratio is the signature of the approximate number system (Halberda & Feigenson, 2008; Izard, Sann, Spelke, & Streri, 2009): Babies can correctly distinguish two pairs of non-symbolic magnitudes with a 1:2 ratio (Xu, Spelke, & Goddard, 2005) and three-year olds with a 3:4 ratio (e.g., 6 and 8 dots). Six-year olds can compare magnitudes with a 5:6 ratio, and this increases to a ratio of 10:11 in adults (Halberda & Feigenson, 2008). Nine-month-old infants seem to notice that 5+5 is not 5 but 10, because these comparisons are based on the easiest ratio of 1:2 (McCrink & Wynn, 2004). Wynn (1992) and Dehaene (2011) demonstrated that, next to approximate representations, infants also have exact representations for numbers, but this is limited to numbers under four. Typically developing children know for instance that 1+1 equals 2 and not 1 or 3, referred

to as subitizing (Wynn, 1992). The early capacity to track small numbers of objects may be conditional to inferring around the age of 3 or 4 that any set, however large, must have a precise number (Dehaene, 2011).

Neuroimaging studies reveal a specific area within the intraparietal lobes, the IntraParietal Sulcus (IPS), to be an important neural region for representing and processing quantity. This area in the brain responds to all the modalities of number presentation, and its activation varies according to whether the numbers are small or large, close or distant (e.g., Dehaene, 2011, Molko et al., 2003; Price et al., 2007). The neural region for processing quantity is tightly linked to the regions for space and time in the parietal brain area (Assel, Landry, Swank, Smith, & Steelman, 2003; Bull, Espy, & Wiebe, 2008; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). A recent study by Gebuis and Reynvoet (2012) demonstrated that comparing non-symbolic magnitudes is not a pure numerical process, but also involves weighting different visual parameters such as stimulus diameter, surface area, and density. They give the daily life example of choosing a train compartment: You will choose the one that looks least dense, without estimating the number of people. In the same vein, it is suggested that relations among magnitudes may arise from the strength of correlations between number and space in the natural environment (Cantlon, 2012). In line with these outcomes, fMRI studies revealed that approximation activates the IPS, but that activation also leaks to brain areas that code for location, size, and time similar to activation caused by visual-spatial tasks (Dehaene, 2011; Dehaene et al., 1999). Later on in development when the mental number line refines, influence of visual-spatial skills also becomes evident on a behavioral level (Dehaene, 2011): When representing numbers on a number line ranging for instance from 0-10 (Laski & Siegler, 2007), mental visual-spatial representations are essential for understanding that the number 9 should be put diametrically opposite 1 and the number 5 in the middle.

Likewise, *working memory skills* may be closely related to numerical development (Dehaene, 2011; Geary et al., 2009), as for instance, Wynn's subitizing tasks with numbers under four demand that the child holds in mind pieces of information presented at different times. Five-month-old infants see one or more toys that are then hidden behind a screen. The babies have to keep this information in mind and compare this to how many toys they see the experimenter add or remove before they can make a decision about whether the presented solution to a sum is correct or incorrect.

We propose that apart from impairments in learning and retrieving arithmetic facts or deficits in executive functions (Wilson & Dehaene, 2007), children with serious delays in learning math may show serious number sense deficits and fail to compare magnitudes (e.g., choosing the largest amount) even when numbers are below 4 (e.g., Von Aster & Shalev, 2007). In those children not only processing of symbolic, but also non-symbolic magnitudes may be affected (Feigenson et al., 2004; Price et al., 2007), probably in combination with visual-spatial and working memory impairments (Geary et al., 2009; Gebuis & Reynvoet, 2012).

If serious math delays relate to a number sense deficit, training basic number sense skills such as comparing amounts might be a way to remediate these math problems. Previous research targeting children with developmental dyscalculia (DD), demonstrated for instance that number line representations of 8-10 year olds can improve by means of an intervention in which children practice locating the correct spot on a number line (Kucian et al., 2011). The only interventions that proved successful in the remediation of dyscalculia though, included children who were able to process magnitudes, but who did so slower than their peers (e.g., Kucian et al., 2011; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009). If the twins indeed demonstrate an inability to compare numbers under four, they may show low responsiveness to an intervention that trains the ability to compare numbers.

Case Report

Nine-year-old monozygotic twin girls were referred to the university clinic for a psycho-educational and neurological examination because of a serious delay in math development and the absence of evidence for response to intervention. Despite a daily individual instructional program and daily individual tutoring during the first two-and-half years of primary education, all attempts to teach the twins basic math skills such as counting, estimating, comparing numbers, and simple addition and subtraction sums up to 10 had failed. The twins continued making errors in counting, and their ability to solve simple sums under ten and memorizing those problems varied per day.

The twins were born very pre-term (Gestational Age: 27 weeks and 5 days) and had a Very Low Birth Weight of 980 gram (N) and 960 gram (J), respectively. Survivors with a VLBW or very pre-term birth (Gestational Age (GA) $\leq$ 33 weeks) are at a substantially greater risk for developmental disorders than children with a higher birth weight, higher gestational age, or term-born children (Aarnoudse-

Moens, Weisglas-Kuperus, Van Goudoever, & Oosterlaan, 2009; Taylor, Espy, & Anderson, 2009). According to a meta-analysis on neurobehavioral outcomes of VLBW children and/or children born very pre-term (Aarnoudse-Moens et al., 2009), these children perform significantly poorer on mathematics, reading, and spelling compared to term-born peers. Combined effect sizes were -0.60 SD for mathematics, -0.48 SD for reading, and -0.76 SD for spelling. Moreover, pre-term birth may intrude on cortical development and the development of brain connectivity or myelination (Sansavini, Guarini, & Caselli, 2011).FMRI data (Isaacs, Edmonds, Lucas, & Gadian, 2001) showed reduced grey matter in the left intraparietal sulcus (IPS) in a preterm group with calculation difficulties at age 15, while a preterm group without calculation problems did not show these brain abnormalities. In addition to grey matter abnormalities, Clark and Woodward (2010) found white matter abnormalities in pre-term born children with poor visual-spatial working memory performances at age six. In this study, the white and grey matter abnormalities were demonstrated at term equivalence age long before cognitive problems emerged.

This study started with a general cognitive assessment followed by assessment of the twins’ math, reading and spelling skills. Subsequently, numerical processing skills were analyzed in a step-wise design, starting with higher-order math skills and ending with the most elementary number sense skills. Data on standardized tests were contrasted with the mean score of the reference group as reported in the accompanying manuals. In so far as standardized tests were not available, the data of the twins were contrasted with data of eight typically developing control children using a variant of the t-test adapted to the comparison of a single participant’s performance to that of a small control sample in single case studies (Crawford & Howell, 1998; Crawford, Howell, & Garthwaite, 1998).

General Abilities

Intelligence. The twins’ intelligence profile as measured with the WISC-III NL 3rd edition (Wechsler, 2005) was extremely disharmonious; N and J’s performance IQ was 61 and 72 respectively which is substantially below the norm, whereas their verbal IQ was within one standard deviation, 87 and 90 respectively. In Table 5.1 an overview of their standardized scores is presented. Their scores on Block Design, Picture Arrangement, Mazes, and Object Assembly were 2 standard deviations or more below the norm. On the subtest Arithmetic, they performed very poor: 3 standard deviations below the norm. Scores on the

subtests Similarities, Coding, Vocabulary, and Comprehension were within the normal range. Working memory was poorly developed according to their low score on the WISC-III subtest Digit Span (cf. Barsky & Siegel, 1992). Assessed with a standardized word span task instead of the digit span test (Leidse Diagnostische Test [Leiden Diagnostic Test]; Schroot & Van Alphen de Veer, 1979), N scored more than 3 standard deviations below the norm (IQEquivalent = 55) but J scored just outside the normal range (IQEquivalent = 82).

Table 5.1
Standardized scores on general cognitive abilities

Subtest	Standardized scores N	Standardized scores J
Block design ¹	1	3
Mazes ¹	5	5
Picture arrangement ¹	4	4
Object assembly ¹	2	3
Arithmetic ¹	1	1
Similarities ¹	11	12
Coding ¹	8	10
Vocabulary ¹	12	8
Comprehension ¹	10	12
Digit span ¹	1	4
Verbal IQ ²	87	90
Performance IQ ²	61	72
Word span ²	55	82

¹ (M = 10; SD = 3). ² (M = 100; SD = 15)

Math skills. The Tempo-Test-Rekenen [rate-based test for math] (de Vos, 2001) with a total of 200 addition, subtraction, multiplication, and division problems of increasing difficulty up to 100 was administered. The test starts with single digit problems and ends with more complex multi-digit problems. Within 3 minutes, children need to solve as many sums as possible. The score is the total of correct sums minus the incorrect ones. Both girls scored among the lowest 10% compared to the age norm group. It was striking that both girls never used a counting strategy (e.g., finger counting) or any other manifest procedure to solve the sums.

Reading and spelling skills. Since Grade 3, the twins had some problems with spelling when words followed complex rules. On a standardized Dutch dictation task, 'PI-dictee' (Geelhoed & Reitsma, 2004) they both scored among the lowest 10% compared to the age norm group, mainly due to errors in complex rules that often included the concepts "short" and "long." An example of a complex rule in Dutch is the short and long vowel: In 'pap' [cereal] 'a' is pronounced short while 'a' in 'wagen' [car] is pronounced long.

A standardized word reading task, 'Eén-Minuut-Test' [one minute test], was administered to assess word reading skills. Within one minute, words have to be read aloud from a list. The standardized score is based on the number of words read accurately, the child's gender, and age (Brus & Voeten, 1973). N and J both scored more than 2 standard deviations above average (standardized scores are 19 and 17 respectively). On the pseudo-word reading test 'Klepel', that assesses how many pseudo-words can be read accurately within 2 minutes (Van den Bos, Lutje Spelberg, Scheepstra, & de Vries, 1994), the twins' standardized scores were 15 (N) and 16 (J), which was more than one standard deviation above the norm.

In summary, the twins' deficit provides us with a rare opportunity to explore the nature of a serious failure to learn math. Combined with failure to make any progress in math, we expected that the twins might have an inability in processing symbolic as well as non-symbolic magnitudes. They might lack any sense of the meaning of magnitudes, represented by deficits in the approximate as well as the small number system, probably as a result of serious visual-spatial and working memory impairments in accordance with their intelligence profiles.

Experimental Studies of Number Sense

The first step in the experimental studies was to test the twins' representations of numerical magnitudes under 10. Estimating the locations of different specific numbers from all parts of the numerical range under 10 is assumed to be a higher-level math skill on which typically developing kindergartners perform well (Siegler & Ramani, 2008). As a critical test the twins located numbers on a number line with 0 on one end and 10 at the other with no other numbers or marks in-between. In this study, eight age-matched typically developing girls participated as a control group (*mean age* = 10.4, *SD* = 3.5 months).

Numerical Magnitude Representations

Material and procedure. Numerical magnitude representations (Laski & Siegler, 2007) were assessed with a computerized version of the *Number Line Estimation Task*, programmed in E-Prime 2.0; see panel I in Figure 5.1. Children marked the numbers 1, 2, 3, 4, 5, 6, 7, 8, and 9, each presented twice in random order, on a line with 0 and 10 printed on the ends (for a detailed description see Siegler & Ramani, 2008; Laski & Siegler, 2007). All estimates were automatically saved to two decimal places. Based on the ratings, each child's linear fit (expressed in R^2) was computed. $R^{2\log}$ represents a logarithmic fit for the data of the 0-10 number line, commonly providing the best fit in preschool-age: Children's estimates exaggerate differences in magnitudes of smaller numbers and compress differences in larger numbers (Siegler & Ramani, 2008; Laski & Siegler, 2007). A transition to a linear fit occurs during preschool and kindergarten. $R^{2\text{linear}}$ is 1, if all numbers are marked exactly on the corresponding spot.

Results. The 8 control girls scored almost perfectly linear: $R^{2\text{linear}} = .99$ for the 0-10 number line. The scores of N and J, both $R^{2\text{linear}} = .72$, were significantly less linear [$t(7) = 25.46, p < .001$ (N and J)]. A paired sample t-test revealed that the linear fit of the control group was significantly higher than the logarithmic fit of .89 [$t(7) = 25.44, p < .001, d = 8.66$]. The difference between the logarithmic [$R^{2\log} = .79$ (N) and $R^{2\log} = .76$ (J)] and linear fit (both $R^{2\text{linear}} = .72$) of the twins was smaller compared to the difference observed in the control group [$t(7) = 14.97, p < .001, d = -35.69$ (N) and $t(7) = 16.81, p < .001, d = -43.80$ (J)]. These results indicated that the twins had not developed a linear representation for number symbols up to 10, but relied more on a logarithmic representation for numbers below 10, which also becomes evident from Figure 5.2. They were able to say the numbers in correct order but did not understand the rank order of the numbers' magnitudes. Both estimated under 5 rather well but underestimated numbers beyond 5.

The twins' poor visual-spatial skills may explain their poor performance on the number line task (Dehaene 2011; Geary et al., 2009). A certain spatial ordering of quantities is necessary when mentally placing numbers on a line: One needs to know for instance that the number 9 should be put diametrically opposite 1 and the number 5 in the middle.

In line with the finding that the meaning of symbols for numbers up to 10 was not obvious to them, we hypothesized that the twins might be unable to understand, approximate and manipulate non-symbolic numbers, and as a

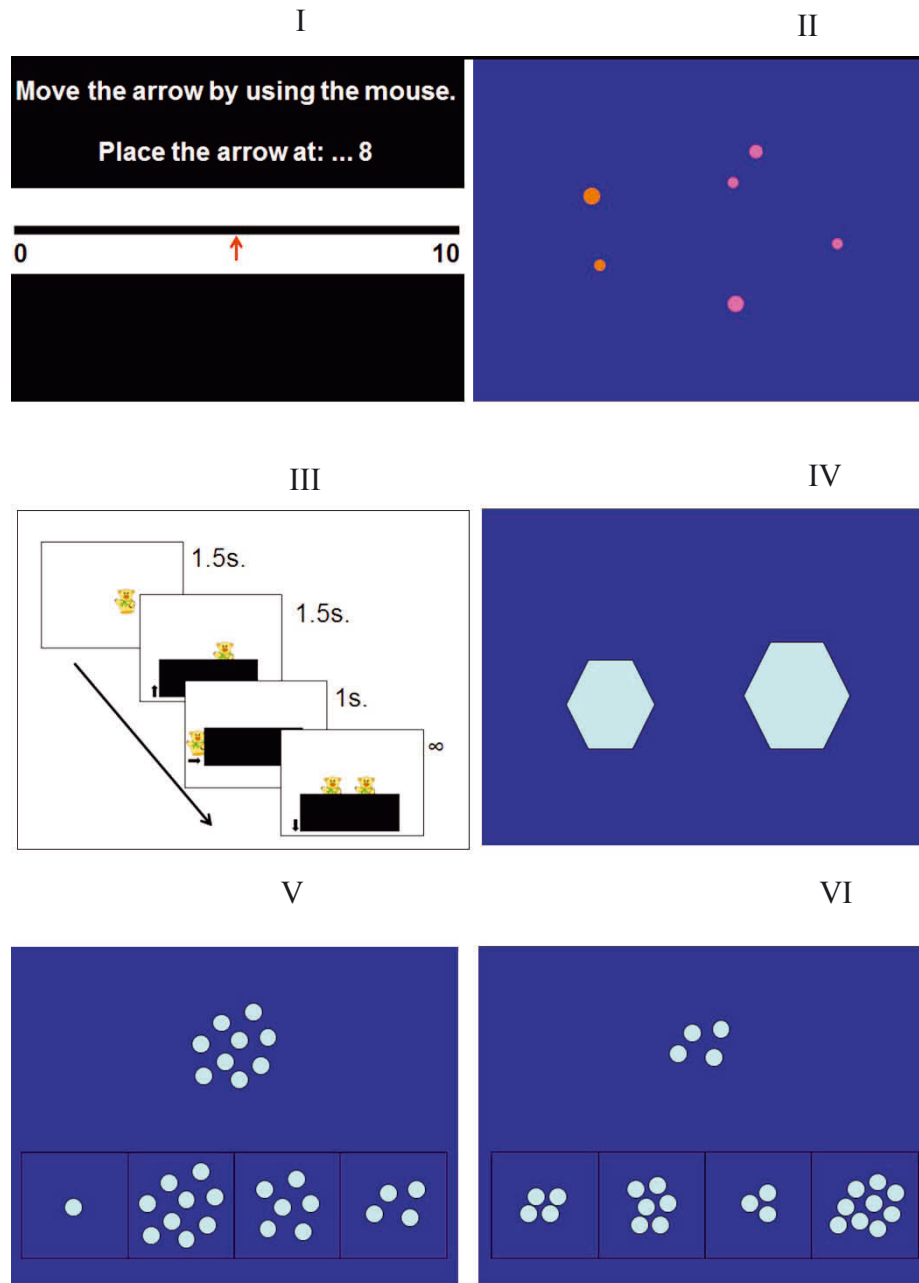


Figure 5.1. Each of the panels illustrates one of six tasks: I Numer Line Estimation; II Magnitude comparison; III Subitizing showing 1+1 equals 2 (Wynn, 1992); IV Magnitude discrimination with solid figures; V equivalence (same arrangement of dots); VI conservation (i.e., different arrangement of dots).

result not connect number symbols to quantities. As a critical test, we tested the hypothesis proposed in the literature that they might have an inability to compare number magnitudes (Halberda & Feigenson, 2008). Secondly, we tested how they would approach a non-symbolic magnitude comparison task, when magnitudes were not processed automatically. Moeller et al. (2009) used an eye-tracker in a dot counting task to test the use of a counting strategy in two boys with dyscalculia. They hypothesized that the two 10-year-old boys with dyscalculia in their study, would show a stronger increase in reaction time (RT) and number of fixations as more dots had to be counted. Compared to the control group, the two boys indeed showed a much steeper regression slope in RT and number of fixations, suggesting that they needed to count at least in some proportion of the trials, whereas the control group processed more automatically, resulting in faster RT's and less fixations.

Numerical Magnitude Comparisons

In line with Moeller et al. (2009), we administered a numerical magnitude comparison task using an eye tracker (*Tobii T120*), to find out whether the twins

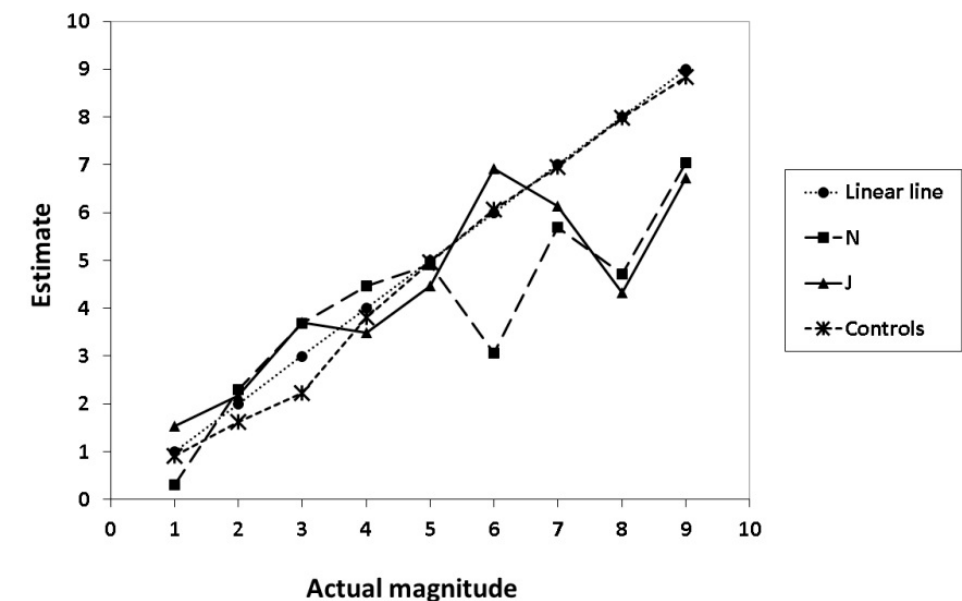


Figure 5.2. Number line scores for controls (asterisks), N (squares), and J (triangles). The linear line (dots) illustrates perfect estimates

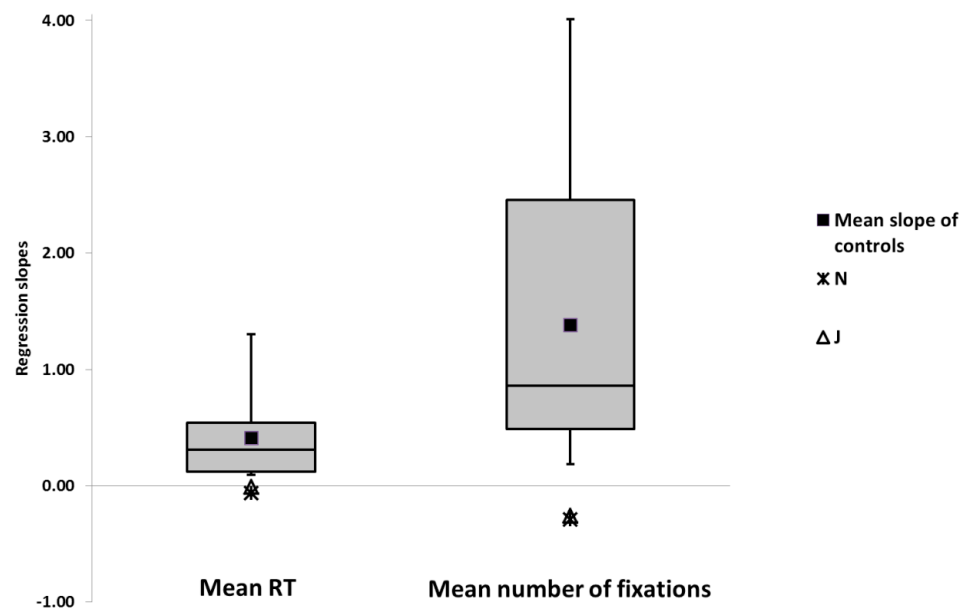


Figure 5.3. Regression slopes for mean RT in seconds (left panel) and the mean number of fixations (right panel) in an eye-tracking task. The asterisks represent N's score and triangles J's score. Shaded areas represent the second and third quartile for controls and the black cuboids the mean slopes. Error bars indicate the lowest and highest slope of the controls.

Table 5.2

Percentage correct, reaction time and mean number of fixations on magnitude comparison eye tracker

Condition	% correct N	% correct J	% correct controls (SD)	RT N	RT J	Mean RT controls (SD)	Mean fix N	Mean fix J	Mean fix controls (SD)
Ratio 1:2	39.60	45.80	95.05 (.05)	2.51	2.24	1.98 (.43)	5.21	6.17	6.09 (1.10)
Ratio 3:4	29.20	45.80	93.23 (.10)	2.57	2.43	2.48 (.99)	5.96	6.25	8.38 (3.09)
Ratio 5:6	33.30	41.70	92.71 (.10)	2.64	2.27	3.08 (1.32)	5.17	5.42	9.56 (3.54)
Ratio 7:8	50.00	66.70	91.67 (.06)	2.27	2.26	3.14 (1.55)	4.50	5.58	10.30 (5.12)

were sensitive to the difficulty of the number comparison tasks. We expected that with increasing ratio (ranging from 1:2 to 7:8), the controls would respond slower and demonstrate more eye-fixations to compare the two sets of dots (Moeller et al., 2009). The twins might show a similar but slower pattern or, in case they were unable to solve such problems, a completely aberrant pattern.

Material and procedure. In this numerical magnitude comparison task children were asked to select the largest set of dots ranging from 1-16 ($n = 96$). Presented ratios were 1:2 ($n = 48$), 3:4 ($n = 24$), 5:6 ($n = 12$), and 7:8 ($n = 12$). In each ratio, all possible dot pairs were presented, therefore n varied among ratios. In presenting sets of dots, surface area, dot diameter, and density varied (cf. Halberda & Feigenson, 2008). Dot color of the left set was orange and of the right set pink. Background color of the slides was blue; see panel II in Figure 5.1. There was no time limit. After the child gave a verbal response (orange or pink), the experimenter pressed the spacebar. Next a smiley appeared (for 1 second) in the center of the screen whereupon the next trial appeared. An eye-tracker was used to make manifest how the twins' approach differed from the control group's approach. The influence of increasing ratio was evaluated by performance (percentage correct), RT (mean duration of eye-fixations), and number of fixations, using Tobii Studio version 2.2.6 (Tobii Technology, 2010). Based on the ratio condition, regression slopes for RT and number of fixations were calculated for each control child and compared to the slopes of the twins (see Moeller et al., 2009).

Results. Descriptive statistics for percentage correct, RT, and number of fixations, split by ratio are displayed in Table 5.2. The control group had a high mean score (96.26% correct). In line with previous findings (e.g., Halberda & Feigenson, 2008), the ratio 7:8 was most difficult for the control group (on average 91.67% correct; see Table 5.2). The twins scored significantly lower than the control group: Overall percentage correct of N and J was at chance and equaled 39.18% and 49.48%, respectively [$t(7) = -20.39, p < .001, d = -21.62$ (N) and $t(7) = -16.71, p < .001, d = -17.72$ (J)]. Also when split by ratio, percentage correct of the twins was at chance in each ratio and significantly lower than in the control group; N for ratio 1:2: $t(7) = -1045.58, p < .001, d = -1109.00$ and J for ratio 1:2: $t(7) = -928.67, p < .001, d = -985.00$; N for ratio 3:4: $t(7) = -603.68, p < .001, d = -640.30$ and J for ratio 3:4: $t(7) = -447.17, p < .001, d = -474.30$; N for ratio 5:6: $t(7) = -560.12, p < .001, d = -549.10$ and J for ratio 5:6: $t(7) = -480.93, p < .001, d = -510.10$; N for ratio 7:8: $t(7) = -654.78, p < .001, d = -694.50$ and J for ratio 7:8: $t(7) = -392.37, p < .001, d = -416.17$.

The control group had increasing RT's as well as increasing eye-fixations when the ratio became more difficult (see Table 5.2), with the longest mean reaction time and highest number of fixations in the ratio 7:8 condition. The twins' RT's and eye-fixations by contrast did not increase with ratio (see Table 5.2), resulting in a flatter slope compared to the controls, that is, falling outside the range of the box plots (see Figure 5.3). Findings thus suggest that the twins tried to solve the problems in the most difficult ratio the same way as in the easiest condition. This is striking as the more difficult ratios, with a smaller difference between numerical magnitudes, take longer to process and more fixations are needed before deciding which dot pair is largest. A shorter reaction time and lower number of eye fixations in combination with the low performance across all ratios [1:2, 3:4, 5:6, 7:8] strongly suggest that the twins failed to implement a strategy to compare amounts and were just guessing. The control children by contrast did have more fixations and a longer fixation duration in the more difficult ratios, as their RT's and eye-fixations increased with ratio. Even though there was no time limit, controls did not count the dots but seemed to compare surfaces covered with dots, the dots' density, and the dots' diameter by moving the eyes between the two sets of dots.

In summary, these findings indicate that the twins were unable to compare non-symbolic magnitudes under 16 (Halberda & Feigenson, 2008), even within the easiest ratio of 1:2. These outcomes thus suggest that the twins' approximate number system was underdeveloped (Dehaene, 2011; Halberda & Feigenson, 2008). Maybe due to underdeveloped visual-spatial skills, they were unable to weight different visual parameters (i.e., dot size, surface area) and therefore might be unable to estimate differences between two sets of dots (Gebuis & Reynvoet, 2012). The question arises whether next to the approximate number system, the small number system is also affected, which implies that they cannot solve exact calculations with smaller amounts (Dehaene, 2011; Wynn, 1992). In a next step, we therefore tested subitizing skills using a test modeled after Wynn's task.

Subitizing

Material and procedure. A digital version of Wynn's subitizing task (1992) was programmed in MS PowerPoint (panel III in Figure 5.1). The tasks consisted of 37 similar addition and subtraction problems with numbers under four. On a computer screen a maximum of 3 bears appears for 1.5 seconds, whereupon the bears are hidden behind a screen. After the bears have been completely hidden

for 1.5 seconds, bears are added or subtracted. During 1 second the child sees bears fly out/in. After 1.5 seconds, the screen is removed (duration 1 second). The result (1 to 3 bears) is then displayed without a time limit and the child has to say whether the displayed answer is correct or not (too many or too few bears). They were not asked to provide the exact answer (e.g., there should be 2 bears).

Results. The twins scored at chance level [38% and 57% correct for N and J], which was significantly below the mean of the control group scoring 94.26% correct [$t(7) = -5.85$, $p < .001$, $d = -6.20$ (N), and $t(7) = -4.19$, $p < .01$, $d = -4.44$ (J)]. There were no response biases, meaning that the presented outcome (either correct or incorrect) and type of problem (addition or subtraction) did not affect the results. Outcomes thus imply that the twins did not know that one bear plus another bear equals two, and not three or four bears (Wynn, 1992), which indicates that they missed exact representations for numbers up to three.

To summarize, the twins had a strong and stable deficit in comparing amounts (up to 16), even when quantities were under four. Results of the subitizing task indicated that the twins' small number system was underdeveloped. However, in the subitizing task, where objects were covered, added or removed, we could not rule out that poor working memory skills might have interfered with solving the addition and subtraction problems (Dehaene 2011). In the number line and magnitude comparison tasks, demands on working memory were lower, because stimuli remained present.

The twins' poor visual-spatial skills may have had an impact, because the bears remained in the same place and the twins had to keep a vivid and realistic image of the objects hidden behind the screen: a kind of mental photography (Dehaene, 2011). Likewise, we argued that visual-spatial skills may have affected the twins' numerical processing skills in the number line and magnitude comparison task (Dehaene, 2011; Gebuis & Reynvoet, 2012). To test seriousness of visual-spatial problems in solving number sense tasks, we used subtests of the magnitude discrimination tests designed by Siegel (1971) with a decreasing visual-spatial component. The first test tapped strongest on visual-spatial abilities: A child must recognize simple size differences by choosing the largest of two solid areas. The ability to recognize equivalent sets of dots is less dependent on visual-spatial skills than magnitude comparison but more so when visual-spatial relationships between dots remain the same. All three tests were programmed in MS PowerPoint (see panels IV, V, and VI in Figure 5.1). In the

control group, subtests IV and V were terminated when the first 10 consecutive items were correct.

Magnitude Comparisons with Differential Influence of Visual-Spatial Skills

Material and procedure. In the first subtest (panel IV in Figure 5.1), the largest of two solid area figures (for instance two rectangles or two circles, differing in size) had to be chosen (80 items in total). This task tested whether the twins were able to compare size of objects. Comparing objects or figures differing in size (e.g., big/small) is basic to ordering and therefore assumed to be an early developing numeracy skill (Torbeyns et al., 2002), typically tapping on visual-spatial abilities. In the second subtest of the magnitude discrimination test (*equivalence*) a dot pair was presented at the top of the computer screen and at the bottom, the child had to select the same amount of dots out of four dot pairs (80 items); Figure 5.1, panel V. Magnitudes ranged from 1-9. Subtest three in Siegel’s battery (*conservation*) was the same as subtest two, with the exception that the same amount of dots presented at the bottom was differently arranged than at the top of the screen (20 items); Figure 5.1, panel VI. Thus in comparison to subtest two, children could not rely on the visual arrangement of dots in this subtest, but instead numerical processing was necessary.

Results. The twins scored significantly below the mean of the control group (see Table 5.3 for mean scores) on magnitude discrimination of solid area figures [$t(7) = -51.15, p < .001$ (N), and $t(7) = -31.25, p < .001$ (J)], which highlights the seriousness of visual-spatial delays. On the equivalence and conservation subtest, the twins scored at chance as well and significantly below the mean of the control group (see Table 5.3 for mean scores): Equivalence [$t(7) = -47.50, p < .001, d = -47.50$ (N), and $t(7) = -48.75, p < .001, d = -48.75$ (J)], and conservation: [$t(7) = -4.49, p < .01, d = -4.49$ (N), and $t(7) = -4.76, p < .01, d = -5.05$ (J)].

In other words, there was no evidence for modulation of number sense scores as a function of the visual-spatial task component. The twins consistently scored at floor and the level of visual similarity did not modulate their performance. The overall low performance, even on the simplest magnitude discrimination task, strengthens the hypothesis that the twins’ poor visual-spatial skills might be at the root of delays in normal number sense.

If the visual-spatial component of the equivalence and conservation subtests was simplified by only presenting numbers under four, the twins scored higher. On equivalence, N and J scored on 27 items that met this criterion 70% and

67% correct, respectively. Similarly, on conservation both scored 80% correct on 5 items under 4. In comparison to the control group, the twins performed significantly better on items with amounts under four, compared to items with amounts of four and higher in both tests [$t(7) = 112.32, p < .001, d = 1907.07$ (N equivalence) and $t(7) = 104.31, p < .001, d = 1645.44$ (J equivalence), and $t(7) = 95.72, p < .001, d = -1386.34$ (N conservation) and $t(7) = 95.58, p < .001, d = -1382.43$ (J conservation)]. This finding may indicate that the twins were to some extent sensitive to the complexity of the visual-spatial component of the task.

Table 5.3
Scores on math skills

Test	Number of items	Scores N	Scores J	Scores controls (SD)
Mental arithmetic (raw score)	200 ^a	13	8	27.2 (reference group from manual)
Number line 0-10	18	R ^{2lin} = .72 R ^{2log} = .79	R ^{2lin} = .72 R ^{2log} = .76	R ^{2lin} = .99 R ^{2log} = .89
Subitizing (% correct)	37	38	54	94.26 (9.07)
Solid figures (% correct)	80	48.75	68.75	100 (0)
Equivalence (% correct)	80	52.50	51.25	100 (0)
Conservation (% correct)	20	50%	45%	90.63 (9.04)

^a maximum score. Score equals the number of correct answers within 3 minutes.

In summary, the findings on the number line task, the eye-tracking magnitude comparison task, the subitizing task, and the magnitude comparison tasks of Siegel indicate that the twins had a serious delay in number sense, in the approximate as well as the small number system (Dehaene, 2011; Feigenson et al., 2004; Molko et al., 2003). All number sense tasks were solved at chance level (Dehaene, 2011; Siegel, 1971; Wynn, 1992). There seemed to be a high degree of specificity in the twins’ developmental number sense delays as differences between verbal and performance IQ suggest. At the root of the twins’ number processing impairments there might be poorly developed visual-spatial skills

(Assel, Landry, Swank, Smith, & Steelman, 2003; Bull, Espy, & Wiebe, 2008; Dehaene, 2011; Geary et al., 2009; Gebuis & Reynvoet, 2012) as well as working memory delays. All number sense tasks included demands on both visual-spatial skills and working memory albeit not to the same extent (Geary et al., 2009). For instance, the demands on working memory might have been stronger in the subitizing task as in this task elements were covered, whereas in the other number sense tasks, elements remained visible (Dehaene, 2011).

Outcomes support the hypothesis that deficits in both numerical systems, the approximate and exact small number systems, can be core problems when pupils have serious math problems (Price et al., 2007). Yet we cannot rule out the possibility that impairments in visual-spatial skills and working memory caused underdevelopment of number sense and that persistence of those impairments interfered with improvement during the years in school.

The question remains whether in such cases core number sense skills can be trained. Previous research showed positive effects of number line training in children with dyscalculia (Kucian et al., 2011; Moeller et al., 2009). However, contrary to the twins in this study, children in these studies had some basic numerical understanding but processed magnitudes slower than typically developing children due to the need to use a counting strategy (e.g., Kucian et al., 2011; Moeller et al., 2009). An intervention was implemented to find out whether the twins were responsive to practicing comparing numbers.

Responses to Intervention

Number Race. In the second half of Grade 3, both girls received, twice weekly, a computer-assisted intervention (Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Wilson et al., 2006; <http://sourceforge.net/projects/numberrace/>) for about three months (N 23 times, J 16 times) under supervision of an undergraduate student. Although there is no consensus about the effectiveness of math intervention programs, the NR game especially aims to train assessment of quantities, the counting routine, the link between symbols and quantities, and the understanding that number and space are linked (Dehaene, 2011; Räsänen et al., 2009). As number comparison skills seem to be a core deficit in case of the twins, this program was chosen. J started the intervention four weeks later than N (resulting in 23 sessions for N and 16 sessions for J).

In the intervention that aimed at comparing amounts and connecting amounts to symbols the twin girls were instructed to select the highest number

from two options presented either as dots, numbers or as addition or subtraction problems (Räsänen et al., 2009; Wilson et al., 2006). Later tasks increased in difficulty due to the use of numbers or addition and subtraction problems. The rest of the week they received care-as-usual including remedial teaching.

During the whole intervention period, N was unable to decide which amount of dots was largest in the NR games, even for numbers below 4. Throughout all sessions, N mostly guessed with the exception of comparing 2 and 4. She thought that 2 dots were more than 4 and stuck to that idea. Attempts for demonstrating the concept of more and less (e.g., counting and then locating the numbers on the number line) were unsuccessful. At the end of the intervention, N's notion of more and less had not improved despite suggestions of the supervisor to count and decide with the help of a number line showing all numbers between 0 and 10.

In the first two levels of the NR (14 levels in total), J often guessed which amount was larger and only counted the dots when encouraged by the experimenter. She benefitted, however, from counting and marking both amounts on the number line when choosing the larger amount. Without a number line, she guessed which of the two options was larger resulting in scores at chance level. Throughout the sessions (see Figure 5.4) her performance showed an upward tendency ($R^2 = .79$; $\beta = .45$) and she reached the highest level possible ($M level = 10$; small addition problems up to 5), different from N ($M level = 7$; comparison

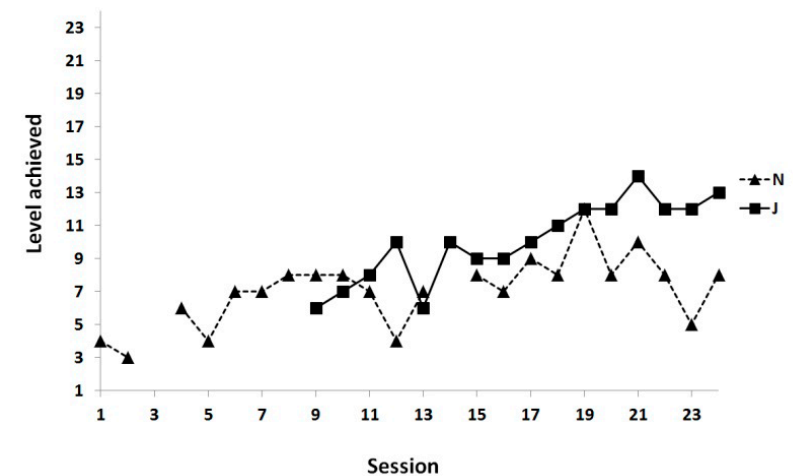


Figure 5.4. Achieved levels of the Number Race game by session, for N (dashed line with triangle markers) and J (solid line with squares).

of verbally spoken numbers up to 9). J outperformed N ($t(23) = 3.14$; $p < .01$; $d = .53$), probably not due to improved magnitude comparison skill but because she was more successful in using additional tools like the number line to solve the games.

Discussion

Are there core deficits that account for problems in acquiring arithmetic skills similar to a phonological deficit in reading? The current study reported on two monozygotic 9-year old twins born very preterm with a VLBW, who seem to have a remarkably underdeveloped approximate and small number system. Both girls fail to understand concepts like bigger/smaller even though they use these words. Most surprisingly, they failed to notice what most young children normally understand without any training, namely that one bear plus another bear equals two, and not three or four bears. They were unable to represent, discriminate, and operate on small numbers under four (Wynn, 1992). Unlike other examples of a number sense deficit described in the literature (e.g., Moeller et al., 2009), the twins were not just slower in number comparisons but completely failed, even within the easiest ratio condition of 1:2. The eye-tracking data revealed that the twins did not show the expected increase in RT and number of fixations by task complexity, whereas the control children did. Outcomes of the control children were in line with previous findings that magnitudes with a small numerical distance are more difficult to compare than magnitudes with a large numerical distance (numerical distance effect; e.g., Halberda & Feigenson, 2008). As the twins scored significantly below the mean on all ratios, outcomes strongly suggest they were unable to compare the sets of dots and were just guessing.

In summary, outcomes imply that both numerical systems, the approximate number system as well as the small number system, were underdeveloped (Dehaene, 2011; Feigenson et al., 2004; Molko et al., 2003), which may explain why further math development was hindered (Dehaene, 2011; Price et al., 2007). Their subitizing deficit in combination with their difficulties in comparing non-symbolic amounts (i.e., knowing what is larger) might explain why they failed on marking numbers on a number line. This typically taps into the ability to compare quantities and relate number symbols to quantities (Laski & Siegler, 2007). The twins fail in solving problems, probably because solving simple problems strongly builds on understanding quantity relations (Krajewski

& Schneider, 2009). When learning sums like $2 + 3$, a child needs to understand that the outcome must exceed 3.

Unlike other studies that report attempts to improve number sense skills, our attempts to enhance quantity comparison skills failed. N remained unable to compare amounts, even when encouraged by the experimenter to count correctly and to look up numbers on a number line. J failed as well in comparing the numbers but, unlike N, she did benefit from applying a counting strategy and using a number line when decisions had to be made about the largest amount. However, J never used these tools spontaneously, but only when she was encouraged and coached by the experimenter in applying these strategies. Thus only one twin benefited somewhat from an intensive training in comparing numbers and locating numbers on a line. Like the two boys with dyscalculia in the study of Moeller et al. (2009), the children with dyscalculia in the study of Kucian et al. (2011) performed slower on number sense tasks, whereas the twins in our case study did not solve number sense tasks beyond chance level.

Visual Spatial and Working Memory Skills

Results corroborate the hypothesis that visual-spatial skills and working memory (like scores on puzzles, object assembly and digit span of the WISC) commonly associated with dyscalculia (e.g., Geary et al., 2009), may be at the root of the twins' number sense impairment. Comparing amounts of dots requires estimating the surface area, stimuli diameter and density, and thus visual-spatial skills (Dehaene et al., 1999; Gebuis & Reynvoet, 2012). As we discussed above, subitizing as assessed in a test modeled after Wynn's task, but other number sense tasks as well, strongly demand working memory (Dehaene, 2011). The results indicate a high degree of specificity in the developmental number sense delay: The twins' score on sub-tests of the WISC-III with a strong visual-spatial and working memory component was substantially below the norm, whereas their score on verbal IQ-tests was within the normal range. In the same vein, the Number Race intervention may not have been effective or only somewhat effective because the twins lacked visual-spatial and working memory skills that are indispensable to compare amounts – the main activity in the Number Race. Other types of training that target visual-spatial and working memory skills might have been more beneficial than the Number Race.

In summary, the current findings corroborate the hypothesis that an inability to weight visual parameters is at the root of impairments in the approximate and

small number system. Likewise, holding information in mind and manipulating that information, may on its own or combined with visual-spatial deficits also be at the root of the ability to solve number sense tasks (Dehaene, 2011; Geary et al., 2009). We speculate therefore that in these specific cases number sense may not normalize until their visual-spatial skills and working memory catch up. It may have consequences for treatment whether or not at the root of delays are visual-spatial and/or working memory deficits. Hence, more important than the putative category 'dyscalculia' is to specify underlying impairments.

Future Directions

The finding that the twins seem to manifest no processing difference in comparing magnitudes with different numerical distance, might point to a weakened parietal representation of non-symbolic magnitudes (Price et al., 2007). According to, for instance Wilson and Dehaene (2007) and Price et al. (2007), at least some children with serious math problems typically show less activation of the parietal cortex while comparing numbers. Likewise, the fMRI studies of Isaacs et al. (2001) and Clark and Woodward (2010) revealed that in children born preterm (in case of the twins at Gestational Age 27) and with calculation problems, grey matter may be reduced in the left intraparietal sulcus (IPS). The IPS is detectable in fetuses around GA (pregnancy week) 26-28. As the twins were born at GA 27, this may have affected prenatal brain development and the IPS in particular. There is also evidence from fMRI studies that during non-symbolic magnitude comparison, nonverbal visual-spatial cerebral networks are activated (Dehaene et al., 1999). As visual-spatial skills are undeveloped, atypical activation of nonverbal visual-spatial cerebral networks could be present in the twins (Clark and Woodward, 2010).

It is also possible that impaired neuronal networks might account for the twins' severe number sense deficit (Kucian et al., 2006) as task performance is mostly dependent on the cooperation of diverse brain areas (Micheloyannis, Sakkalis, Vourkas, Stam, & Simos, 2005). A consolidated neuronal network is necessary when diverse brain areas are involved in task performance. Weaker activation of a network could be the result of non-reinforced synaptic connections due to lack of experience (Kucian et al., 2006), which is not very plausible here. Next to weak connections between brain areas, intraparietal disconnection after damage to a focal region of subcortical white matter might cause math problems (Rusconi et al., 2009; Sansavini et al., 2011). As a next step in analyzing the twins' math problems it might make sense to test structural connectivity between brain areas.

Chapter

6

General discussion

The current study extended research on a set of interrelated cognitive processes that play a vital role in organizing and regulating information thereby affecting children's ability to take advantage of natural learning experiences and the school curriculum. Working memory, attention shifting, and inhibitory control problems – hereafter indicated as executive functions (EF) – may all underlie the organization and regulation of information in novel or challenging situations. The following four research questions were targeted in the current thesis:

1. Do EF skills interfere with benefiting from informal experiences that are known to stimulate early literacy development?
2. Do EF skills, beyond other basic learning skills such as visual-spatial development and speed of processing, explain why early literacy and early numeracy co-vary substantially?
3. Are EF skills *causally* related to early developing academic skills in the age range from preschool through first grade?
4. Can delays in EF skills play an important role in the development of severe delays in math development?

Effects of EF on Academic Development

A main conclusion of the current thesis is that effects of EF on academic skills in preschool and kindergarten are rather small; the studies revealed low to moderate correlations among attention control, inhibition, and short-term memory on the one hand and early numeracy and literacy skills on the other hand. In study 1 (chapter 2) correlations for instance ranged from $r = .19$ (inhibition and letter knowledge) to $r = .43$ (short-term memory and vocabulary). However, after controlling for parent print exposure, book reading frequency, book-cover recognition, and intelligence, only short-term memory remained a significant predictor of vocabulary. In the second study (chapter 3) neither attention control nor short-term memory explained overlap among early numeracy and early literacy skills, after taking into account effects of other learning skills (visual-spatial skills, speed of processing, shared storybook reading and vocabulary). EF skills thus seem less important for early academic development than is commonly claimed (Bodrova & Leong, 2006; Diamond & Lee, 2011; Duncan et al., 2007; McClelland et al., 2007; NICHD, 2003; Valiente et al., 2010; Welsh et al., 2010), and effects of EF skills on early academic skills decrease when other skills that may affect learning are controlled (Raghubar et al., 2010).

Another main conclusion is that short-term memory in preschool, as precursor of working memory in older children (Bull et al., 2008), was the strongest EF correlate of early academic skills. In the first study (chapter 2), only short-term memory predicted vocabulary over and above shared book reading and intelligence. When controlled for shared book reading and intelligence none of the EF skills predicted letter knowledge. Likewise, in the second study (chapter 3), short-term memory explained co-variance among early literacy and numeracy when we controlled for significant effects of visual-spatial skills, vocabulary, and phonological awareness. Effects of attention control became non-significant after the other covariates were taken into account. In the third study (chapter 4), changes in short-term memory predicted changes in math, reading, and writing development, whereas changes in inhibition were solely related to changes in literacy development. The twin study also revealed evidence for working memory as a cause of their number sense impairment: The twins performed poorly on two working memory tasks (digit span backwards and word span). Especially in the subitizing task, poor working memory may have influenced task performance, because objects were covered, added or removed (Dehaene, 2011). Even though in other number sense tasks (number line and magnitude comparison) stimuli remained present, these tasks also made an appeal to working memory skills because information had to be stored and manipulated (Geary et al., 2009). Apparently, holding information in mind is more important for developing early academic skills than attention and inhibitory control. One of the explanations could be that before and during preschool a child's attention is controlled by caregivers and teachers, whereas from Grade 1 and up children often do tasks independently (i.e., they listen to instructions and make a working plan without assistance). Tasks may then make a strong appeal to attention and inhibitory control.

In line with this reasoning, the first study for instance clearly demonstrated that preschool EF skills do not moderate effects of shared book reading on vocabulary and letter knowledge; notwithstanding children's EF skills, shared book reading was beneficial for early literacy development. Shared book reading might be an activity with lower demands on EF, because it is highly structured. During whole group instructions much more distracters are present, thereby making a stronger appeal to EF skills.

Contrary to previous studies suggesting that EF is stronger related to early numeracy than to early literacy (Blair & Razza, 2007; Duncan et al., 2007;

McClelland et al., 2007), no differences in the strength of the effects of EF on numeracy and literacy development from preschool through first grade were found in the current thesis. Differences in measures may account for this apparent contradiction. In the meta-analysis of Duncan et al. (2007), for instance, questionnaires like the Child Behavior Checklist were used as indicator of attention control. Contrary to EF tests, questionnaires measure EF skills in real life situations which may reveal results that differ from clinical assessments of EF (Isquith, Crawford, Espy, & Gioia, 2005). More importantly, the age of the children in the meta-analysis was 5 or higher (Duncan et al., 2007), whereas in our studies the focus was on a younger age-range. Especially for more advanced math skills, EF skills such as attention and inhibition may be required (Assel, Landry, Swank, Smith, & Steelman, 2003).

Not EF Skills but Visual-Spatial Skills were the strongest Correlates of Academic Skills

Surprisingly not EF skills but visual-spatial skills were the strongest correlates of both early numeracy and early literacy in the second study (chapter 3). Likewise, the twin case study (chapter 5) highlighted the importance of visual-spatial skills for numeracy development, next to effects of working memory (Dehaene, 2011; Geary et al., 2009). The twins' severe number sense impairment may be explained by an impairment in visual-spatial and working memory skills. Moreover, their irresponsiveness to a training in comparing amounts could be due to severely impaired visual-spatial skills and working memory, since comparing amounts strongly appeals to these skills (Dehaene et al., 1999; Gebuis & Reynvoet, 2012). In similar cases, it might therefore be useful to find out whether training of visual-spatial and memory skills may result in improvements in elementary numerical processing.

Why are visual-spatial skills so important for academic development? In the early years of life, visual-spatial abilities enable identifying and/or discriminating objects for instance by their shape (i.e., a square versus a circle) (Ruff & Rothbart, 2001). As long as children cannot name letters and numbers, they are able to distinguish them by shape (Bull, Espy, & Wiebe, 2008; Dehaene, 2011). Also later on in numeracy and literacy development, visual-spatial abilities remain important. When linking numbers to quantities, visual-spatial skills enable visualizing amounts (Krajewski & Schneider, 2009). In the same vein, visual cues enable young children to familiarize with letter forms (Levy, Gong, Hessels,

Evans, & Jared, 2006) which is a precursor for learning letters (Both-de Vries & Bus, 2014).

As the current thesis highlighted the importance of visual-spatial skills for academic development, it may be useful to investigate whether visual-spatial skills are underdeveloped when delays in early numeracy or literacy development are present.

Are EF Skills Causally Related to Academic Skills?

In this research, no effects of preschool EF on academic outcomes in Grade 1 were found (with the exception of the significant effect of preschool inhibition on Grade 1 reading). At an early age, EF skills may be rather variable and only into adulthood skills may become more stable (Davidson et al., 2006; Diamond, 2002). Children with early delays in EF may catch up during preschool and, consequently, may not experience any difficulties with learning to read and write as a result of delays in preschool EF skills. In other words, changes in EF skills may be better predictors of academic skills in Grade 1 than are one-time assessments.

Interestingly, the longitudinal study containing repeated measures for EF and academic skills (chapter 4), revealed that changes in EF from preschool to end of first grade (memory and inhibition) were significantly related to changes in academic skills over the same period (with the exception that changes in inhibition were not related to changes in math development). Relations were positive, indicating that growth in EF from preschool to first grade is causally related to growth in academic skills. The advantage of a Fixed Effect Analysis is that the analysis focuses on changes over time; effects of unmeasured *time invariant* covariates are thus taken into account, thereby strengthening inferences about causality. In simple regression analysis, it is impossible to control for all possible confounder variables, because many covariates that may cause spurious outcomes are unknown. It thus can be concluded that growth in the ability of maintaining and manipulating information in memory, and growth in the ability of ignoring distracters are causally related to growth in academic development (Diamond & Lee, 2011). In other words, it seems not possible to predict reading and math outcomes in Grade 1 from preschool EF skills, but growth in EF skills can predict academic development.

Maturation of the prefrontal cortex from preschool to Grade 1 might be one of the reasons why EF development is a more reliable predictor of academic

outcomes than are single measurements (Diamond, 2002). Another plausible hypothesis is that EF skills are implicitly trained when children practice numeracy and literacy skills at home or at school (Bodrova & Leong, 2007; Morgan-Borkowsky, 2012). Bodrova and Leong (2007), for instance, show how shared storybook reading can promote EF skills when caregivers set strict behavioral constraints: Children are for instance instructed to listen without interrupting the reader. By setting rules children practice how to suppress impulsive reactions.

Implications for the School Curriculum and Early Intervention Programs

Study 3 revealed that children's EF skills rapidly change during preschool and kindergarten (Davidson et al., 2006). Moreover, these changes may result in improvement in academic development. Whatever the explanation may be for these changes in EF, it seems questionable that early EF interventions are needed, because children often catch up as a result of maturation or activities in school and at home. Moreover, the effect sizes of preschool EF skills on early academic skills were rather small. This outcome thus challenges the need of explicit training of EF skills. Only if delays in EF persist, training might be useful and effective (Diamond & Lee, 2011).

Training working memory skills seems most useful, as working memory was in general the strongest correlate of early numeracy and literacy skills. In the long run, working memory was causally related to math, reading, and writing development, whereas inhibition was solely related to the literacy outcomes. Compared to inhibition, working memory thus seems to have a broader effect on academic development. There is some evidence that working memory can be enhanced at preschool-age by means of training (Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). There is however no consensus about positive transfer effects on for instance early academic skills. From a review of working memory training studies, Klingberg (2010) concludes that especially when delays in academic skills are present, training of working memory may be an effective remediation tool. Melby-Lervåg and Hulme (2013), by contrast, conclude in their recently published meta-analysis that effects of working memory training are only present over a short period of time. They found no transfer effects on early academic skills such as math and word decoding. These contradicting outcomes may be due to methodological differences: Outcomes of Melby-Lervåg and Hulme (2013) are based on a quantitative meta-analysis approach, whereas Klingberg (2010) only reviewed several experimental studies

on working memory training, without applying statistical analyses. However, as most of the existing training studies are done with children older than 9 or with adults (Melby-Lervåg & Hulme, 2013), there is a clear need of experimental studies testing in primary school-age whether training of working memory can enhance performance in early academic skills.

Interestingly, early literacy and numeracy skills remained moderate to strong predictors of academic development when controlled for background variables, EF skills and other cognitive skills. Early intervention programs that aim to improve early numeracy (e.g., Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Siegler & Ramani, 2009) or early literacy skills (e.g., Van der Kooy-Hofland, Bus, & Roskos, 2011) are therefore indispensable for the prevention of learning impairments in Grade 1 and beyond. In the same vein, it is important that already early in the school curriculum teachers should pay attention to emerging literacy as well as to emerging numeracy skills, which is not commonly done: Compared to early literacy, less attention is paid to early numeracy skills in preschool and kindergarten (Ginsburg, Lee, & Boyd, 2008). The results of study 2 confirm that numeracy and literacy skills co-vary, which may imply that training of early literacy skills may promote early numeracy skills, and, vice versa, training of early numeracy may promote early literacy. This result also implies that it is important to monitor numeracy development when delays in literacy are apparent, and literacy development should be monitored when delays in numeracy are present.

Conclusions

The current thesis revealed that EF skills in preschool-age were not related to academic outcomes in Grade 1, and they only moderately predicted emerging academic skills in preschool. However, the finding that changes in EF skills relate to changes in academic skills supports the hypothesis that EF is causally related to academic development. These findings thus imply that children's improvement in academic skills partly depends on improvement in executive functions. It is however still unknown whether executive functions develop independently of academic skills or as intrinsic elements of literacy and numeracy development. We hypothesize that children with delays in EF are able to catch up due to maturation, home, and school influences.

Secondly, effects of early EF on early academic skills were not only small, but also differential; effects of short-term memory, attention, and inhibitory control on early academic skills differed. Short-term memory appeared to be the strongest EF predictor for both literacy and numeracy.

Overall, the findings of this series of studies show that EF is at best one of many factors that explain academic development. Early academic skills were much stronger predictors of academic development than were EF skills. After controlling for early EF and other background variables, early academic skills remained moderately strong predictors of academic outcomes in Grade 1. Compared to other basic cognitive skills, EF skills were rather weak predictors of academic development. In particular visual-spatial skills appeared to be much better predictors of early literacy and numeracy development compared to the effects of EF skills.

The current thesis thus challenges the general assumption that delays in early academic skills can be explained by early EF skills (Espy et al., 2004; McClelland et al., 2007; Welsh et al., 2010). In fact, EF skills may be less vital for explaining delays in early academic skills than is commonly assumed. However, the fact that growth in EF is related to growth in academic skills makes plausible that EF in addition to numerous other variables is a causal factor.

Future Directions

The EF measures applied in the current study all target specific EF skills, referred to as *situationally constrained processes* (Isquith et al., 2005). These tests assess executive functions in a more clinical setting and do not assess executive behaviour in real-life situations such as executing tasks in the classroom. Assessments such as the BRIEF (Behavior Rating Inventory of Executive Function) may give more specific information about a child's self-regulatory behaviour at home or in school (Isquith et al., 2005). Using both types of instruments may give a more valid indicator of regulatory behaviour in all kinds of situations.

Secondly, there is a need of more experimental research in the domain of academic development. One of the results was that early numeracy and early literacy skills co-vary substantially. In line with this outcome, intervention studies could test whether training of literacy skills may also lead to improvements in numeracy skills, and, vice versa, whether training of numeracy may lead to improvement in literacy.

Effect studies should also test whether training of early academic skills positively affects EF development, and, vice versa, whether training of EF is beneficial for academic development. It should be taken into account that transfer effects may be small and specific, especially because the strength of the relation among EF and academic skills differed by the sub-skills measured. In other words, training specific early numeracy or literacy skills may only lead to small improvements in certain sub-EF skills.

Finally, the importance of visual-spatial skills for academic development should be further explored. Visual-spatial skills can be trained (Mathewson, 1999), but it is unclear whether training of visual-spatial skills also leads to improvements in numeracy and literacy.

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Samenvatting (Summary in Dutch)

Jonge kinderen verschillen niet alleen in kennis, maar ook in de manier waarop ze leren. Sommige kinderen zijn bijvoorbeeld goed in staat afleiders zoals rumoer in de klas te negeren, terwijl andere kinderen snel afgeleid zijn. Dit soort verschillen kan erop duiden dat *executieve functies* (EF) meer of minder ontwikkeld zijn.

Onderzoek heeft aangetoond dat executieve functies een rol spelen bij het leren van vroege lees- en rekenvaardigheden, zoals letters en cijfers, rijmen en tellen (Duncan et al., 2007; McClelland et al., 2007). Het is echter nog steeds onduidelijk 1) *hoe* executieve functies het leren van kleuters beïnvloeden en 2) of onderontwikkelde executieve functies in de kleuterklas op de lange termijn gevolgen hebben voor leren lezen, schrijven en rekenen. Concreet is in het kader van deze dissertatie onderzocht of 1) kinderen meer profiteren van voorlezen naar mate hun executieve functies beter ontwikkeld zijn, 2) of executieve functies kunnen verklaren waarom de vroege lees- en rekenontwikkeling zo sterk samenhangt, 3) of er een *causaal* verband is tussen executieve functies en lees- en rekenvaardigheden en 4) of executieve functies een rol spelen bij grote ontwikkelingsachterstanden in leren rekenen.

Volgens Diamond (Davidson, Amso, Anderson, & Diamond, 2006) zijn werkgeheugen, inhibitie, aandacht controle en cognitieve flexibiliteit onderdelen van executieve functies. Het *werkgeheugen* stelt je in staat om informatie vast te houden terwijl je tegelijkertijd de bewerking uitvoert. Beginnende rekenaars moeten bijvoorbeeld de rekenopgave ('2 erbij 3') onthouden terwijl ze tellen of doortellen. *Inhibitie* houdt in dat je in staat bent om irrelevante prikkels of associaties te onderdrukken. Denk bijvoorbeeld aan kleuters die hun vinger al opsteken als de leerkracht nog niet klaar is met de vraag. Hun snelle reacties zijn vaak associatief ("Juf, ik heb ook een konijn"). De derde component is *cognitieve flexibiliteit*. Dat wil zeggen dat je in staat bent om regels toe te passen in nieuwe situaties en dat je van regel kunt wisselen. Kinderen die hiermee moeite hebben, maken bijvoorbeeld veel fouten als optel- en aftreksommen door elkaar staan en ze kunnen moeite hebben met een dictee waarbij ze verschillende spellingregels tegelijk moeten toepassen. 'Je aandacht erbij kunnen houden' is een belangrijke voorwaarde voor alle executieve functies. Een kind dat snel is afgeleid, vindt het vaak moeilijk om associatieve reacties of irrelevante prikkels te onderdrukken en loopt daardoor het risico belangrijke informatie te missen.

In de eerste studie is onderzocht of kinderen die moeite hebben om informatie te onthouden (werkgeheugen) en problemen hebben met het onderdrukken van irrelevante impulsen (inhibitie), in mindere mate profiteren van voorlezen waardoor ze een achterstand oplopen in woordenschat en letterkennis. Aan het onderzoek hebben 228 kleuters (in de leeftijd van 4 jaar en 3 maanden tot 4 jaar en 9 maanden) meegewerkt. Naast werkgeheugen, inhibitie en intelligentie zijn vroege leesvaardigheden getest: woordenschat en letters benoemen. Er is tevens in kaart gebracht hoe vaak de kinderen worden voorgelezen.

Traditionele vragen aan ouders/verzorgers zoals “hoe vaak leest u uw kind voor per week?”, kunnen een vertekend beeld geven van de voorleesfrequentie. Ouders zijn zich ervan bewust dat voorlezen wenselijk is en vullen een hogere frequentie van voorlezen in dan daadwerkelijk het geval is. Om dit probleem te ondervangen is een prentenboeken-herkenningslijst samengesteld op basis van top 100 lijsten van meest verkochte en uitgeleende prentenboeken. Wie vaker wordt voorgelezen is vertrouwd met een groter aantal prentenboeken.

Uit deze studie kwam naar voren dat alle kinderen profiteren van voorlezen. Er zijn geen aanwijzingen dat de positieve invloed van voorlezen op zowel woordenschat als letterkennis sterker is bij kinderen met goede executieve functies en, omgekeerd, zwakker bij kinderen met zwakke executieve functies. Kennelijk slagen kinderen erin om aandachtig naar een verhaal te luisteren ook als ze in andere situaties snel afgeleid zijn. Executieve functies verklaren wel verschillen in woordenschat (3.61 procent) en letterkennis (2.56 procent), al zijn de effectgroottes klein. Kennelijk leren kleuters met zwakke executieve functies minder letters en woorden in andere situaties dan voorlezen.

In een tweede studie is onderzocht of executieve functies kunnen verklaren waarom kleuters die een achterstand hebben in leesontwikkeling, vaak ook achterlopen in rekenen (Krajewski & Schneider, 2009). In deze studie is daarom getoetst of werkgeheugen en aandacht verklaren waarom de ontwikkeling van vroege lees- en rekenvaardigheden zo nauw samenhangt. Rijmen, ontluikend schrijven, kennis van de schrijfrichting en letters kunnen onderscheiden van andere tekens waren de indicatoren voor vroege leesvaardigheden. Vroege rekenvaardigheden zijn getest met simpele sommetjes tot 10 in verhaalvorm (“*Marieke heeft 2 appels. Joep geeft haar nog 1 appel. Hoeveel appels heeft Marieke nu?*”) en met materiaal (“*Kijk hier liggen 2 stenen. Nu zet ik het scherm ertussen. Let goed op: ik doe er 1 steen bij. Hoeveel stenen liggen er nu. Je mag het met je eigen stenen laten zien en mij dan vertellen hoeveel het er zijn.*”).

Uit deze studie kwam naar voren dat werkgeheugen voor een klein deel verklaarde waarom vroege lees- en rekenvaardigheden zo sterk samenhangen. Aandacht verklaarde daarentegen de overlap tussen rekenen en lezen niet. Visueel-ruimtelijke vaardigheden verklaarden de meeste overlap wat niet verrassend is. Bij het leren van letters raken kinderen het eerst vertrouwd met de onderscheidende visuele kenmerken van letters (Both-de Vries & Bus, 2014). Om de betekenis van cijfers te leren moet je een mentale voorstelling van hoeveelheden kunnen maken (Krajewski & Schneider, 2009). Voor zover woordenschat een factor van betekenis was, betrof het alleen rekenen in een verhaalcontext (Fuchs et al., 2006).

In de derde studie is getoetst of veranderingen in executieve functies gerelateerd zijn aan veranderingen in lees- en rekenontwikkeling. Executieve functies zijn op jonge leeftijd nog volop in ontwikkeling (Diamond, 2002) en vroege achterstanden kunnen door rijping van de prefrontale cortex (het gebied in de hersenen dat geassocieerd wordt met executieve functies), maar ook door leerervaringen thuis of op school ingelopen worden. Vroege achterstanden in executieve functies hebben daarom niet noodzakelijk gevolgen voor leren lezen en rekenen in groep 3. Als executieve functies een factor van belang zijn, zou groei in executieve functies daarentegen wel gerelateerd moeten zijn aan groei in lees- en rekenvaardigheden. Deze hypothese is getoetst door executieve functies en lees- en rekenvaardigheden herhaald te meten.

Resultaten van herhaalde metingen aan het begin van groep 1 en aan het einde van groep 3 bevestigden dat executieve functies gemeten in groep 1 geen voorspeller zijn van achterstanden in leren lezen, schrijven en rekenen in groep 3. Groei in executieve functies van begin groep 1 tot einde groep 3 was daarentegen een vrij sterke voorspeller voor de lees- en rekenontwikkeling tussen groep 1 en 3. Dit duidt op een *causaal* verband tussen executieve functies en lees- en rekenvaardigheden: als executieve functies verbeteren, dan verbeteren lees- en rekenvaardigheden eveneens, en andersom, als de ontwikkeling in executieve functies stagneert, ontwikkelen lees- en rekenvaardigheden minder snel.

In de vierde studie is een *case study approach* gebruikt om te onderzoeken of achterstanden in executieve functies ten grondslag kunnen liggen aan ernstige leerproblemen. Een 9-jarige eenjarige tweeling (twee meisjes) was doorverwezen naar het ambulatorium van de Universiteit Leiden in verband met een ernstige achterstand in rekenen. Werkgeheugen en visueel-ruimtelijke vaardigheden waren onderontwikkeld, maar op andere gebieden verliep de ontwikkeling

normaal. De achterstand in rekenen was dermate ernstig dat speciale toetsen ontworpen zijn om getalbegrip te meten: het vergelijken van twee objecten (welk rondje is groter), het vergelijken van hoeveelheden tot 4 (*subizing*) en het vergelijken van hoeveelheden tot 20 (waar zie je meer stippen). De scores van de tweeling zijn vervolgens vergeleken met de scores van acht normaal ontwikkelende 9-jarige meisjes.

Daaruit kwam naar voren dat de tweeling een ernstigere achterstand had in de ontwikkeling van getalbegrip dan doorgaans het geval is bij rekenproblemen. Beide meisjes misten elementaire noties van hoeveelheden. Ze zagen bijvoorbeeld niet onmiddellijk wat meer is: een of twee paperclips. Het is aannemelijk dat door dit probleem de verdere rekenontwikkeling stagneerde. Vergelijken van hoeveelheden doet in meer of mindere mate een beroep op werkgeheugen en visueel-ruimtelijke vaardigheden, die beide volgens scores op subtests van de WISC-III NL 3rd edition (Wechsler, 2005) onderontwikkeld waren bij de tweeling. Het is daarom aannemelijk dat hun ernstige ontwikkelingsachterstand in getalbegrip het gevolg was van de achterstanden in werkgeheugen en visueel-ruimtelijke vaardigheden.

Een training specifiek gericht op het vergelijken van steeds grotere hoeveelheden (Wilson et al., 2006; <http://sourceforge.net/projects/numberrace/>) had enig effect bij een van beide meisjes, maar alleen als ze er telkens aan herinnerd werd de hoeveelheden te tellen en met behulp van de getallenlijn te bepalen welk getal groter was. De ernstige achterstand in werkgeheugen en visueel-ruimtelijk inzicht kan verklaren waarom de interventie niet geleid heeft tot hogere scores op de tests voor getalbegrip. Vergelijken van hoeveelheden zoals stippen doet immers een sterk beroep op beide vaardigheden (Dehaene, 2011; Gebuis & Reynvoet, 2012).

Conclusies

Op basis van de vier studies kan worden geconcludeerd dat executieve functies een beperkte rol spelen bij de vroege lees- en rekenontwikkeling. Executieve functies gemeten in groep 1 zijn een matige voorspeller van vroege lees- en rekenvaardigheden in groep 1, maar geen voorspeller voor lees- en rekenvaardigheden in groep 3. Veel betere voorspellers van leren in groep 3 zijn vroege lees- en rekenvaardigheden en visueel-ruimtelijke vaardigheden in groep 1. Deze uitkomsten nuanceren de algemene aanname dat achterstanden in lees-

en rekenontwikkeling verklaard kunnen worden door achterstanden in vroege executieve functies. Anderzijds levert het onderzoek wel enige aanwijzingen op dat ontwikkeling van executieve functies een rol speelt in de vroege lees- en rekenontwikkeling. Veranderingen in executieve functies zijn gerelateerd aan veranderingen in lees- en rekenvaardigheden tussen groep 1 en groep 3 wat een causaal verband ondersteunt: Als de executieve functies verbeteren, verbeteren ook de lees- en rekenvaardigheden. Wellicht ondersteunt dit resultaat ook de theorie van Leong en Bodrova dat ontwikkeling van executieve functies en ontwikkeling van academische vaardigheden nauw verweven zijn; effectieve training van academische vaardigheden impliceert training van executieve functies.

Dankwoord (Acknowledgements)

Graag wil ik iedereen bedanken die op welke wijze dan ook een bijdrage heeft geleverd aan de voltooiing van mijn promotieonderzoek.

In het bijzonder gaat mijn dank uit naar de 228 kinderen, de scholen en leerkrachten die mee hebben gewerkt aan mijn onderzoek. Ik bewaar goede herinneringen aan de vele contactmomenten met de kinderen. Ook wil ik alle studenten bedanken die hebben meegewerkt aan het project. Mede dankzij jullie inzet was het mogelijk zoveel kinderen te testen.

Mijn begeleiders, met name professor Bus en dr. de Jong, wil ik bedanken voor hun inzet. Ik waardeer het zeer dat jullie zoveel tijd hebben genomen om mee te denken. Jullie kritische blik leidde altijd weer tot nieuwe inzichten.

Beste collega's, bedankt voor jullie waardevolle bijdrage aan mijn project. De support die ik van jullie heb mogen ontvangen heeft me veel goed gedaan.

Ten slotte wil ik mijn vrienden, ouders, broer en schoonfamilie bedanken voor hun steun en vertrouwen. Lieve Franc, dat je onvoorwaardelijk achter me stond heeft me gestimuleerd bij de voltooiing van dit proefschrift. Lennart, Élodie en Franca, jullie geven me steeds weer positieve energie.

Curriculum Vitae

Neeltje J. Davidse was born on November 19, 1981 in Gouda, the Netherlands. She completed her secondary education (Atheneum) in 2000 at the Coenecoop College in Waddinxveen. Hereafter, she studied Language- and Culture Studies at Utrecht University. After finishing her Master's degree in Language Development and Variation in 2004, she started Pedagogical Sciences at the same university, followed by a Master's degree in Learning Problems in 2006. In September 2006 she started a PhD project at the institute for Education and Child Studies at Leiden University examining the role of executive functions in early academic development.

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