A journey towards mathematics

Effects of remedial education on early numeracy

Sylke Toll

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A journey towards mathematics

Effects of remedial education on early numeracy

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(met een samenvatting in het Nederlands)

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General introduction

"Do not be troubled by your difficulties with mathematics.
I can assure you mine are much greater." – Albert Einstein

Mathematical proficiency is one of the most important core targets in primary education. Experiencing difficulties in learning mathematical abilities can have far-reaching consequences for the daily life and the future school career of a child. Early identification of children at risk of developing math problems or even difficulties enables earlier treatment for these children, which can have positive consequences for their lives for many years thereafter (Clements & Sarama, 2011). Early numeracy in kindergarten is one of the key targets for early identification of at-risk children (Dowker, 2005). In this dissertation, early numeracy is defined as a set of particular skills, including (verbal) counting and knowing number symbols, that a child should have mastered before starting to learn basic mathematical calculations in first grade (Gersten, Jordan, & Flojo, 2005). For most children, learning these skills is a natural process that is guided by (in)formal learning in the home and kindergarten environments (e.g., Ginsburg, Lee, & Boyd, 2008). The research in this dissertation focuses on children whose early numeracy abilities do not develop spontaneously while following the regular kindergarten curriculum, and therefore tend to remain behind throughout their schooling (e.g. Duncan et al., 2007). By examining low early levels of numeracy as an important precursor of delayed or disturbed mathematical development, and identifying several predictors in early numeracy learning and testing the effect of remedial intervention for children lagging behind in early numeracy, these studies will provide new evidence about the importance of early numeracy in the early school career of children.

The importance of early numeracy

The central concept in this dissertation is the concept of early numeracy. Early numeracy involves the general understanding of numbers (Gersten, Jordan, & Flojo, 2005; e.g., Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006), and can be divided into several skills, such as verbal and resultative counting, knowing number symbols, recognizing (un) structured quantities, discerning number patterns, comparing size and magnitudes and estimating quantities (e.g., Gersten et al., 2012; Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). Early numeracy can be seen as an important prerequisite for being successful in mathematics (Jordan, Kaplan, Ramineni, & Locuniak, 2009), and should not be confused with number sense. While some authors (e.g., Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012) use the terms number sense and early numeracy interchangeably in order to indicate the subset of numerical-related skills, number sense in this dissertation refers to pre-verbal and innate ability (Butterworth, 2005).

Research has shown that young children develop a relatively powerful everyday sense of these early numeracy skills before beginning primary school (Clements & Sarama, 2007). Most children already have a spontaneous and sometimes explicit interest in numerical ideas. By the end of kindergarten, many children have a solid if not yet fully mature early numeracy understanding, even when they have not received formal instruction (Geary, 2000). Not all children, however, develop this informal knowledge. It has been established that children with inadequate early numeracy skills, who are already staying behind by the age of 5 years old and not receiving any remedial assistance during kindergarten, are hardly capable of catching up with their typically developing peers during primary school. Evidence based on longitudinal studies classifies these children as being at risk of developing mathematical learning difficulties at a later stage (e.g., Morgan, Farkas, & Wu, 2009; Stock, Desoete, & Roeyers, 2010). Determining the timing and persistence of early numeracy difficulties in kindergarten is an important identifier for those most at risk for math learning difficulties from first to fifth grade. Above-mentioned studies indicate the importance of early numeracy as a core part of the curriculum that is taught to young children in kindergarten, either in a playful setting or in more task-structured learning activities.

Predictors of early numeracy development

Early numeracy development takes place mainly in the period between children being toddlers and formal education in first grade. During this period, other skills are also developing rapidly. From (longitudinal) research on typically achieving children, it is known that these other skills, such as language and working memory, can identify early numeracy in kindergarten and math skills at the beginning of primary school (Cirino, 2011). These underlying factors are often divided into domain-general, or general cognitive resources such as language, intelligence and working memory, and domain-specific predictors, such as quantity discrimination, subitizing, or the use of a mental number line (Passolunghi & Lanfranchi, 2012; Welsh, Nix, Blair, Bierman, & Nelson, 2010). Studies focusing on predictors in early numeracy, particularly those studying children with insufficient skills, however, are rather scarce. Since children with inadequate early numeracy skills are at risk of developing mathematical learning difficulties at a later stage, it is interesting to gain better insight in the predictors of early numeracy in children within this interest group.

Domain-general predictors

One important domain-general skill that has made a unique contribution to early numeracy development in the kindergarten years is language acquisition. It has been well documented that children entering kindergarten differ in their language and early numeracy skills (Fuchs, Geary et al., 2010), and that these skills, like other cognitive skills, are likely to influence each other during development (Schmittel & Bass, 2012). In general, it is assumed that language is one of the main inputs for learning and that for this reason, the acquisition of early numeracy skills is highly dependent on language (e.g., Hooper, Roberts, Sideris, Burchinal, & Zeisel, 2010; Romano, Babchishin, Pagani, & Kohen, 2010). Therefore, it has been argued that adequate language skills are a prerequisite for learning early mathematics (Aiken, 1972; Dehaene, Piazza, Pinel, & Cohen, 2003). Considering that the above-mentioned studies reveal and acknowledge the linguistic challenges of teaching and learning mathematics, it is surprising that relatively little is known about the relations between kindergartners' oral language skills and early numeracy proficiency in particular, and especially for at-risk children with low early numeracy. However, one part of basic oral language that has been hypothesized as being especially important for the development of mathematical ability is the type of language that includes math-related notions such as *more*, *less*, *higher*, and *lower* that can be used to compare or classify objects or amounts, but also concepts as *whole* or *half*, or more spatial concepts as *below* or *above* (Pruden, Levine, & Huttenlocher, 2011). In this dissertation, these are referred to as examples of math-related language (Greenes, Ginsburg, & Balfanz, 2004). It has been shown that some children experience particular difficulties in this specific math language (Ginsburg, 1972; Schleppegrell, 2010) and therefore it has been repeatedly suggested that language and early numeracy skills may be linked because understanding of certain specific language terms is inherently necessary for the completion of basic mathematical tasks (e.g., Sarnecka & Gelman, 2004). This indicates that specific math language might facilitate the use of numerical concepts (Gelman & Butterworth, 2005; Halberda, Taing, & Lidz, 2008), and hence, should be taken into account when examining the predictors of early numeracy.

The other domain-general predictor that will be examined in this dissertation is working memory. Working memory refers to the ability to store and manipulate information simultaneously (e.g. Baddeley, 1986; Baddeley & Hitch, 1974; Just & Carpenter, 1992). It is also understood, more precisely, as the ability to store information temporarily and revise it in the light of new incoming information. In research on working memory, the multi-component model, initially proposed by Baddeley and Hitch (1974), remains useful. The model comprises an attention supervisory system – the *central executive* – which is aided by two subsidiary slave systems – the *phonological loop* and the *visuospatial sketchpad*. A third slave system – *the episodic buffer* – subsequently added to the model, is assumed to be a limited-capacity temporary storage system capable of integrating information from a variety of sources (Baddeley, 2000). Within working memory, a distinction can be made, which is done in this dissertation, between verbal and visual – including visuospatial – working memory (Alloway, Gathercole, & Pickering, 2006). This basic modular structure of working memory has proven to be stable and measurable by the time a child reaches the age of four (Alloway, Gathercole, Kirkwood, & Elliott, 2008; Gathercole, Pickering, Ambridge, & Wearing, 2004).

Working memory underpins a range of higher-order cognitive abilities, including mathematics and early numeracy (e.g., Vukovic & Siegel, 2006), and is considered important for such performances because incoming information must be stored and manipulated during these activities (e.g., Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Swanson, 2011). Performance on early numeracy and math tasks involves simultaneous and sequential processes of perceiving, coding, and interpreting information in different modalities which can be facilitated by working memory processes (e.g., De Smedt et al., 2009). Studies specifically examining the relationship between working memory and early numeracy skills in kindergarten (e.g., Espy et al., 2004; Kroesbergen, Van de Rijt, & Van Luit, 2007; Kyttälä, Aunio, & Hautamäki, 2009) show the importance of identifying working memory characteristics in the early development of mathematical cognition (Klein & Bisanz, 2000). Even at a young age, children constantly need to revise their stored information during the execution of early numeracy tasks. Welsh and colleagues (2010), for example, conclude that working memory, and other domain-general cognitive skills such as paying attention, make unique contributions to the prediction of kindergarten numeracy achievement.

In their review, Raghubar, Barnes, and Hecht (2010) note that many recent studies support the notion that working memory is related to and important for early numeracy outcomes, but that there is no consensus as to whether verbal or visual working memory is a better predictor of early numeracy. While some studies show that measures of verbal working memory, rather than measures of visual working memory, are strongly correlated to children's performance in prerequisites in mathematics (Noël, 2009), other studies have shown that having a visual working memory is also strongly correlated to this (e.g., Krajewski & Schneider, 2009a). However, the empirical evidence shows that there is an influential relationship between the age of the children and the role of visual and verbal working memory. Although the results are not straightforward, visual working memory has frequently been found to play an important role in the numeracy performance of young children aged 4 to 7 (e.g., Holmes & Adams, 2006), whereas verbal working memory has been repeatedly related to the math performance of older children aged 8 to 10 (McKenzie, Bull, & Gray, 2003). However, the findings of studies of children of all ages suggest that visual working memory may be recruited for the learning and application of new mathematical skills and concepts, whereas verbal working memory may come into play after a math skill has been learned (Raghubar et al., 2010). For example, the results of Kyttälä, Aunio, Lehto, Van Luit, and Hautamäki (2003) suggest that verbal working memory skills may be more generic in terms of supporting mathematical skills during primary school, whereas visual working memory may be more specific to early mathematical learning. In addition, Bisanz, Sherman, Rasmussen, and Ho (2005) found that visual working memory was the best predictor of early math performance in kindergarten, but not in first grade.

Knowledge of the contribution of the two working memory components to early numeracy in children with math difficulties is limited, because understanding of which aspects of working memory are deficient in children with math difficulties is obscured by the lack of precise knowledge of the particular strategies and processes that the child brings to bear on working memory tasks (possibly as a function of age and language) and by the lack of any theory that links these working memory processes to particular aspects of mathematical learning and performance (Raghubar et al., 2010). Nevertheless, Swanson and Jerman (2006) state that limitations in verbal working memory characterize children with math difficulties. This is confirmed by another study (Wilson & Swanson, 2001), showing verbal working memory as being a better predictor of mathematical computation than visual working memory in this interest group. Controversially, McLean and Hitch (1999) conclude that visual aspects of working memory are important factors in poor early mathematics.

It appears that limited working memory skills constitute a high risk factor for educational underachievement for school-aged children across the primary school years (Alloway, Gathercole, Kirkwood, & Elliott, 2009). General and specific deficits in working memory components are often present in children with dyscalculia (Geary, Hoard, Nugent, & Byrd-Craven, 2008; Schuchardt, Maehler, & Hasselhorn, 2008). Deficits in verbal working memory ability, for example, can disrupt the representation and articulation of numbers during the counting process (McLean & Hitch, 1999), which leads to secondary deficits in numerical processes (Zamarian et al., 2006). Assuming that working memory deficits can be an explanation for struggles in the mastering of early numeracy skills, children with both limited working memory skills and low early numeracy are a special interest group among children with low early numeracy abilities. Insight in the performance of this specific group can make a considerable contribution to general knowledge about the gaps at-risk children experience in their early numeracy learning. To this end, in this dissertation, special interest is given to children with limitations in their working memory capacity.

Domain-specific predictors

Previous research suggests that skills such as the ability to compare quantities, the ability to recite a counting sequence, or the ability to recognize number symbols are domain-specific predictors of early numeracy development. In this dissertation, discussing the domain-specific predictors will be limited to examining the influence of comparison skills, which is the ability to discriminate between magnitudes, either in non-symbolic quantities (i.e., dots) or in symbolic representations (the number symbols). The distinction between symbolic and non-symbolic comparison skills (Desoete et al., 2012) is based on the triple code model of Dehaene (1992; 2001), which distinguishes between three different types (so-called codes) for number representations; the analog magnitude code (semantic knowledge about the proximity and relative size of quantities), the auditory verbal code (the ability to enumerate the counting row), and the visual code (Arabic number representations). Dehaene (2001) hypothesized that all children are born with an innate understanding of non-symbolic quantity representations and that this can be assessed as early as the first months of life (Feigenson, Dehaene, & Spelke, 2004). Evidence for the existence of such a system was found in infants (Wood & Spelke, 2005; Xu, Spelke, & Goddard, 2005), but also at later ages in studies showing preschoolers being able to compare and add large sets of elements without counting (e.g., Barth et al., 2006). During early childhood, especially in the kindergarten years, the development of symbolic knowledge is based on increasing experience with number words (verbal code) and number symbols (visual code). Eventually, these new symbolic skills are gradually integrated with existing nonverbal knowledge, resulting in more complex cognitive representations in which number symbols and words are connected to quantity representations (Dehaene, 2001; Krajewski & Schneider, 2009b; Mundy & Gilmore, 2009; Mussolin, Mejias, & Noël, 2010). The symbolic comparison task used in this dissertation demands knowledge of the number symbols per se, along with a higher-order ability to connect the meaning of the symbols to their corresponding quantity.

Whether non-symbolic or symbolic skills are more important for early numeracy and math development is still the subject of much discussion. Results from some studies emphasize the importance of non-symbolic skills and state that non-symbolic skills provide meanings for number words and number symbols which are needed in all math tasks. According to these studies, non-symbolic understandings of magnitude form a necessary precondition for learning to associate a perceived number of objects with symbolic number words or number symbols (Von Aster & Shalev, 2007). There are several correlational studies that show quantity discrimination in relation to an understanding of mathematical operations (Desoete & Grégoire, 2006; Gersten et al., 2005; Jordan et al., 2006). Furthermore, relations were found between non-symbolic skills and math performance for children of 5 to 8 years old (Desoete et al., 2012; Gilmore, McCarthy, & Spelke, 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011), indicating that non-symbolic skills are preconditions for higher order mathematical abilities.

In contrast, results from other studies show that non-symbolic skills play a subordinate role in learning math in contrast to the important role of symbolic skills (LeFevre et al., 2010). Moreover, several studies showed that symbolic skills predict math performance in children aged 6 to 8, or that an effect of non-symbolic skills on math performance was mediated by symbolic skills (Holloway & Ansari, 2009; Kolkman, Kroesbergen, & Leseman, 2013).

For children with specific mathematical disabilities, difficulties were found in comparing Arabic number symbols, but not on comparing dot collections (Rousselle & Noël, 2007), indicating that these children are only impaired in accessing number magnitude from symbols rather than in processing quantities. Also Iuculano, Tang, Hall, and Butterworth (2008) conclude that low numeracy is not related to a poor grasp of magnitudes, but rather to a poor understanding of the number symbols, suggesting that the symbolic skills of children might be more important than the previously developed quantitative abilities. But although no consensus as to whether non-symbolic or symbolic skills are more important can be reached within a certain period of time, the importance of including domain-specific comparison skills in studies of early numeracy has been generally endorsed.

Early numeracy support

Supporting numeracy-related learning among children of 3 to 5 years old has a positive effect on the lives of these children for many years thereafter (Clements & Sarama, 2011). Therefore, a growing body of research focuses on the possibility of stimulating the early numeracy development of young children. This has led to ample evidence that early numeracy can be enhanced through structured intervention (e.g., Griffin, 2004; Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005). Empirical evidence centers around curricular interventions implemented over the long-term, such as Building Blocks (Clements, Sarama, Spitler, Lange, & Wolfe, 2011), Big Math for Little Kids (Greenes et al., 2004) and Mengen, Zählen, Zahlen (Krajewski, Nieding, & Schneider, 2008). Studies have also shown that extra-curricular activities can stimulate different domain-specific skills to support the early numeracy skills of kindergartners. Siegler and Ramani (2009), for example, found positive results for improving numerical representations by playing linear board games, based on the idea of Siegler and Booth (2005) that studying number line estimation is a useful means of learning about early numeracy because both require the approximation of magnitudes. Furthermore, the results of other studies have provided evidence that promoting the type of early abstract thought that is involved in seriation and conservation (e.g., Pasnak et al., 2009) as well as supporting the counting sequence (Fuchs, Powell et al., 2010) can enhance kindergartners' numeracy abilities.

Since it is generally accepted that children with low early numeracy skills can be at a disadvantage compared to their typically developing peers, it is remarkable that less information is available about the effects of interventions specifically designed for kindergartners at risk of poor mathematics outcomes. Nevertheless, there are some randomized control trials that assess intervention efficacy for at-risk kindergartners. In most of these studies, children from low-economic status families, who are classified as being at-risk, made significant gains in early numeracy achievement as a target of remedial intervention (Baroody, Eiland, & Thompson, 2009; Dyson, Jordan, & Glutting, 2013; Fuchs et al., 2013; Jordan et al., 2012). However, in a limited number of studies, children were detected as being at-risk based on their early numeracy abilities. In the experiment carried out by Van de Rijt and Van Luit (1998), for example, children with early numeracy ability below a certain criterion-score on an early numeracy test were the interest group of the study. The results of that study showed that it is possible to stimulate the development of early mathematical competence among young poor arithmetic achievers, which is congruent to the results from other studies (Aunio, Hautamäki, & Van Luit, 2005; Kamii, Rummelsburg, & Kari, 2005; Kroesbergen & Van Luit, 2003; Van Luit & Schopman, 2000).

Thus, the results of experimental studies have confirmed the importance of effective numeracy instruction and of receiving additional assistance and instruction in kindergarten – particularly for children with low early numeracy performance (Gersten et al., 2005). Such interventions, which aim to accelerate the early numeracy ability of kindergartners scoring below average, can be used as components of a prevention system within kindergarten in order to ensure minimal delays at the start of first grade. Fuchs, Fuchs, and Compton (2012) describe this prevention system as a multilevel, or multi-tier, system where the regular kindergarten curriculum is offered on the first level. Within the educational setting, screenings are periodically conducted in order to identify children at risk of weak learning outcomes. At the second level of the system, those children identified as weak performers can receive intensive intervention, which is often offered in small groups. The purpose of this prevention system is two-fold (Fuchs et al., 2012). The first aim is to reduce problems in learning outcomes (and the need for special education) drastically, as well as the negative long term effects, which occur when children leave school without the skills they need to function in their afterlife, and the restricted opportunities in the transition from primary to secondary education. The second (complementary) aim of the multilevel system is to identify children with math learning disabilities (Butterworth, Varma, & Laurillard, 2011), as non-responders to valid interventions. With regard to this second aim, it is assumed that a certain proportion of children at risk (about 5%, a percentage corresponding to the percentage of children with a learning disability) will not respond to time-limited evidence-based intervention. For this reason, a multilevel prevention system is referred to as responsiveness-to-intervention (RTI; Fuchs et al., 2012).

For the purpose of the studies described in this dissertation, the program *The road to mathematics* (Van Luit & Toll, 2013) has been developed especially for children lagging behind in early numeracy. This program aims to teach low-performing kindergartners a range of basic numerical concepts and math-related language, providing them with the meaning of numbers through structured activities, and, therefore, to simplify the transition to math education in first grade. *The road to mathematics* addresses a wide range of skills, divided into ten domains, and in doing so offers children a foundation upon which they can build as they enter into first grade. In Chapters 5, 6, and 8 of this dissertation, a description of the program will be given. In these chapters the theoretical background, the program structure, and the three main characteristics and the ten offered domains will be discussed.

Aims and outline of this dissertation

The above-mentioned studies thus point to the importance of early numeracy as a basic part of our mathematical development, revealing several predictors, or underlying factors, in early numeracy learning, and underlining the need for remedial support with a strong focus on early numeracy skills to at-risk kindergartners. The studies in this dissertation contribute to this growing body of knowledge about early numeracy development in kindergartners at risk of developing math learning difficulties and have three main aims. The three aims were addressed in seven research-based articles (see Figure 1.1 for an overview of the outline of this dissertation). The articles as shown in this dissertation may slightly differ from the published or submitted articles.

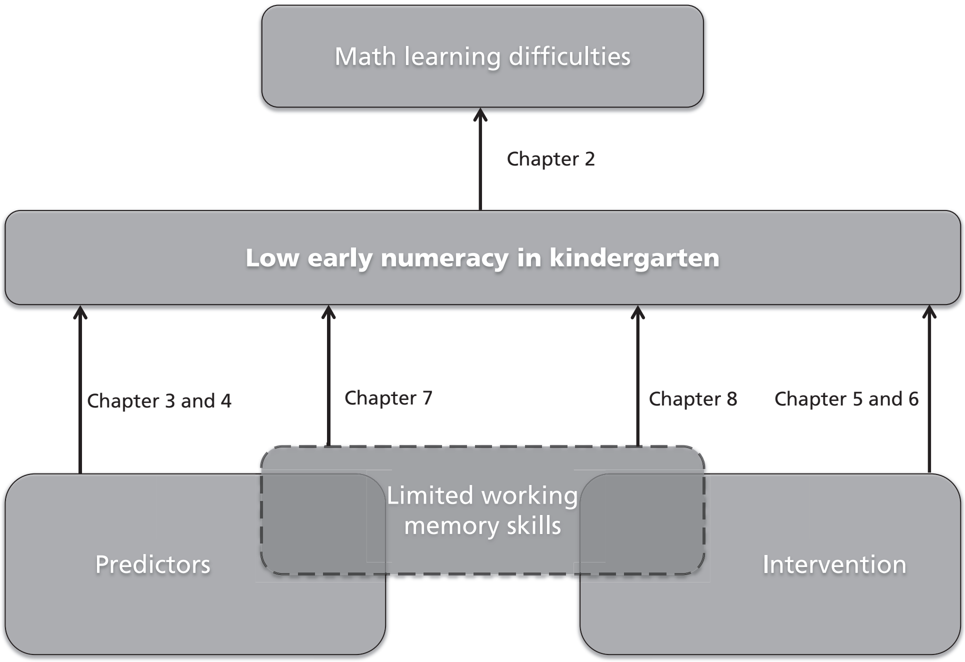

Figure 1.1 Outline of this dissertation.

The first aim was to examine the impact of early numeracy diversity and executive functions as precursors to math learning disabilities in first and second grade. In Chapter 2 the results of a longitudinal study in which this first aim was addressed, are reported. Discriminant analyses showed that both early numeracy – referred to in this chapter as preparatory mathematical abilities – and working memory, rather than shifting or inhibition, were important precursors of math learning disabilities. These results set the stage for the other two aims of this dissertation.

The second aim of the dissertation was to unravel the development of early numeracy and to identify the factors that may contribute to either a successful or a disturbed development of early numeracy. This aim builds on the current idea that early predictors in math learning difficulties can be addressed as key components in remedial programs and interventions preventing children from not falling further behind. Establishing the usability of remedial programs is related to the third aim of this dissertation.

The third aim was to develop and revise a specific remedial intervention for early numeracy and to test whether this program could effectively accelerate the development of early numeracy throughout kindergarten. Both aims were addressed in a large longitudinal study. In this study, 1,040 children were followed from the first year of kindergarten until halfway through first grade (two years). The children were tested at five different time points with different tests being used to measure various mathematical, cognitive and language skills. Based on their performance, at the first time point, the children were classified into an above average group, which functioned as a reference group, and a below average group. The children in the below average group were then randomly assigned to one out of three conditions. Children classified as being in two of these conditions received intensive intervention during the 1.5 year or the 0.5 years with reference to the program *The road to mathematics*. The third condition was the control condition.

Chapter 3 explains a growth modeling approach to investigating the contribution of (non-)symbolic comparison skills, visual and verbal working memory, and specific math language to the development of early numeracy skills in weak performing kindergartners (those scoring below the 15th percentile). Chapter 4 includes a more detailed focus on how specific math language mediates the developmental relationship between general language and low early numeracy skills throughout kindergarten. In both chapters structural equation modeling was performed on the data from the first four time points (from halfway the first year of kindergarten until the end of the second year of kindergarten).

Prior to the longitudinal study, the third aim was addressed in a pilot study testing the effectiveness of a shortened version of *The road to mathematics*. In Chapter 5, the results of the pilot study are reported. In this study, children with a pretest numeracy score falling below the 50th percentile were matched and randomly assigned to an 8-week-intervention group and a control group. Although the sample was relatively small, the results looked promising and gave rise to a larger longitudinal intervention project. Chapter 6 focuses, taking the multilevel structure into account, on the direct and transfer effects of *The road to mathematics* at post-test (end of the second year of kindergarten) and at follow-up (halfway first grade) stages. Furthermore, chapter 5 and 6 examine whether intervention effects are similar for poor achieving children (scoring below the 25th percentile) and children scoring below average (between the 25th and 50th percentile), in order to reveal information about which children benefit from intervention.

In order to provide more in-depth insight in the early numeracy development of at-risk kindergartners, and thus to increase the completeness of this dissertation, two more studies are described. Both studies focus on children with limited working memory skills, because these children are a special interest group among children with low early numeracy skills. Chapter 7 reports on two studies exploring the difficulties these children experience in performing early numeracy tasks. In Chapter 8, the effectiveness of the program *The road to mathematics* is assessed with particular regard to children with (specific) limitations in their working memory resources. Both chapters are based on the data from the first three time points (from halfway through the first year of kindergarten until halfway into the second year of kindergarten). In Chapter 9, which consists of a general discussion, the results of the seven empirical chapters are summarized and discussed and conclusions regarding early numeracy skills in kindergartners at risk of developing math learning difficulties are drawn.

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Executive functions as predictors of math learning disabilities

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Abstract

In the past years, an increasing number of studies investigated executive functions as predictors of individual differences in mathematical abilities. The present longitudinal study was designed to investigate whether the executive functions shifting, inhibition, and working memory differ between low achieving and typically achieving children, and whether these executive functions can be seen as precursors of math learning disabilities in children. Furthermore the predictive value of working memory ability compared to preparatory mathematical abilities was examined. Two classifications were made, based on (persistent) mathematical ability in 1st and 2nd grade. Repeated measures analyses and discriminant analyses were used to investigate which functions predicted group membership best. Group differences were found in performance on one inhibition and three working memory tasks. The working memory tasks predicted math learning disabilities, even over and above the predictive value of preparatory mathematical abilities.

Introduction

Many children in elementary school experience problems in learning mathematical skills. The prevalence is estimated at 6–7% (Geary, 2004), or even 17.9% including combined reading and mathematical disabilities (Dirks, Spyer, Van Lieshout, & De Sonneville, 2008). Sometimes these problems are only diagnosed after some years of math education, during which these children's mathematical difficulties increase (Desoete, Roeyers, & De Clerq, 2004). An early identification of children at risk of developing mathematical difficulties would enable earlier treatment of these children. In addition, detailed knowledge of the type of difficulties these children experience would enable an intervention that is suited to the (im)possibilities of each individual child. One possible target for early identification of at-risk children, which we investigated in the current study, is executive functioning. Executive functions are the higher control functions that involve regulation of thinking and behavior. They are the routines responsible for monitoring and regulation of cognitive processes during complex cognitive tasks (Gilbert & Burgess, 2008; Miyake et al., 2000; Van der Sluis, De Jong, & Van der Leij, 2007; Zamarian et al., 2006).

In research of executive functions the multi-component model of working memory proposed by Baddeley and Hitch (1974) has continued to be useful. The model comprised an attentional control system, the 'central executive', aided by two subsidiary slave systems, the 'phonological loop' and the 'visuospatial sketchpad'. Later, a third slave system was added to the model: the episodic buffer, which is assumed to be a limited-capacity temporary storage system that is capable of integrating information from a variety of sources (Baddeley, 2000). When analyzing the central executive, Baddeley (1996) and Baddeley and Della Salla (1996) specified three component functions: selective attention, switch attention and the need to access and manipulate information in long-term memory. The three executive functions used in this study: shifting, inhibition, and working memory, are based on this specification of component functions. Shifting is defined as the ability to switch between sets, tasks, or strategies; in other words the disengagement of an irrelevant task set and the subsequent initiation of a new, more appropriate set. Inhibition is the ability to suppress dominant, automatic, or prepotent responses in favor of more goal-appropriate responses. Working memory, or updating, is defined as the ability to monitor and code incoming information, and to update the content of memory by replacing old items with newer, more relevant, information (Miyake et al., 2000; Van der Sluis et al., 2007). The distinction in these three lower-level and relatively well-defined executive functions is often used (Miyake et al., 2000; Van der Sluis et al., 2007). The three functions have proved to be separable but dissociable components; they do not share the same underlying ability commonality, but are also distinguishable (Miyake et al., 2000). The functions follow different developmental trajectories during childhood (Klenberg, Korkman, & Lahti-Nuuttila, 2001). Research has shown that working memory (Baddeley & Hitch, 1974) and updating show a large overlap. In a factor analysis, updating and working memory measures loaded on the same factor (St Clair-Thompson & Gathercole, 2006), probably because working memory tasks and updating tasks share the requirement to store information and to revise this in the light of new information (Van der Sluis et al., 2007). In the present study we included tests from both research traditions (one updating task and two working memory span task) and refer to these by the broader term working memory (WM).

A problem in measuring executive functions is the task impurity problem (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Miyake et al., 2000; Van der Sluis et al., 2007). Because executive functions regulate other cognitive processes, assessments of executive functions implies that non-executive cognitive abilities are also measured (Hughes & Graham, 2002; Van der Sluis et al., 2007). In addition, executive tasks often require more than one executive function (Van der Sluis et al., 2007). One method to overcome this problem is the use of control tasks: performance on an executive task is compared to performance on a control task, in which all non-executive aspects of the task are the same but the executive demands are much lower (Van der Sluis et al., 2007).

Executive functions have been hypothesized to underlie a range of higher-order cognitive abilities, including mathematics (Bull, Espy, & Wiebe, 2008; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi, Vercelloni, & Schadee, 2007; St. Clair-Thompson & Gathercole, 2006; Van der Sluis, De Jong, & Van der Leij, 2004; 2007). It is believed that shifting, inhibition, and WM each contribute differentially to mathematical performance. Shifting ability is believed to be involved in mathematical performance by supporting alternation between strategies and sub-solutions in multi-step mathematics problems (Andersson, 2008; Van der Sluis et al., 2007). Bull et al. (2008) found that the ability to shift between mental sets predicted mathematical achievement. In addition, a number of studies have reported poorer shifting abilities in children with mathematical disabilities (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; McLean & Hitch, 1999; Zamarian et al., 2006). However, other studies did not find a relationship between shifting and mathematical abilities (Espy et al., 2004; Van der Sluis et al., 2004). Blair and Razza (2007) found no relation between shifting and mathematical abilities in three-to-five-year-old children either, but did find a prominent relationship between inhibition and mathematical ability. This relationship has been found in more studies (e.g., Mazzocco & Kover, 2007; St Clair-Thompson & Gathercole, 2006) and has been explained by the suggestion that during mathematical problem solving immature strategies and task-irrelevant information must be inhibited. Indeed, a lack of inhibition has been reported in children with lower mathematical ability (Bull et al., 1999; Bull & Scerif, 2001). However, other studies did not find a direct relationship between inhibition and mathematics. Van der Sluis et al. (2004; 2007) found that children with mathematical problems experienced no difficulties with inhibition or shifting per se, but only with a complex executive task that required the combination of these two executive functions. In addition, Bull and Scerif (2001) only found a relationship between mathematics and an inhibition task in which numerical contents were present, and no such relationship between mathematics and the regular Stroop-task, in which the name of a color is printed in a not denoted color that has to be named (Stroop, 1935).

Finally, WM is considered important for mathematical performance because information from long term memory must be stored and manipulated during mathematical problem solving (Andersson, 2008). In addition, deficits in working memory ability can disrupt the representation and articulation of numbers during the counting process (McLean & Hitch, 1999), which lead to secondary deficits in numerical processes (Zamarian et al., 2006). In their review, Raghubar, Barnes, and Hecht (2010) noted that many recent studies support the notion that working memory is related to and important for mathematical outcomes. Indeed, many studies found a relationship between WM, or the related concept of updating, and mathematical or counting ability (Bull et al., 2008; Mabbott & Bisanz, 2008; Kroesbergen et al., 2009; Passolunghi, Mammarella, & Altoè, 2008; Passolunghi et al., 2007; Schuchardt, Maehler, & Hasselhorn, 2008; Vukovic & Siegel, 2010).

Most of these results refer to single measurements. However, both executive functions and mathematics are skills that develop strongly during childhood and may influence each other mutually. Longitudinal studies are still scarce, but Welsh, Nix, Blair, Bierman, and Nelson (2010) showed that working memory was related to later preparatory math performance in kindergarten, even when controlling for earlier numeracy skills. Van der Ven, Kroesbergen, Boom and Leseman (2012) found that growth in working memory was significantly related to growth in mathematics in children in grades 1 and 2. Furthermore, De Smedt and colleagues (2009) found that working memory was significantly related to mathematics achievement in 1st and 2nd grade.

Besides executive functions, preparatory mathematical abilities, such as the ability to subitize small quantities, to discern number patterns, to compare numerical magnitudes and estimate quantities, to count, and to perform simple number transformations (Gersten, Jordan, & Flojo, 2005), are often found as a strong predictor of later mathematical performance (e.g., Jordan, Glutting, & Ramineni, 2010; Locuniak & Jordan, 2008; Morgan, Farkas, & Wu, 2009; Stock, Desoete, & Roeyers, 2010).

The aim of the present study was to investigate whether executive functions can identify children with later mathematical difficulties, and whether this predictive value adds to the predictive value of preparatory mathematical abilities in kindergarten. More specifically, it was investigated whether it is possible to predict poor mathematical abilities in 1st and 2nd grade on the basis of the executive functions in 1st and the beginning of 2nd grade. In order to answer this question, this study was twofold. First, the development of the executive functions of children at risk for mathematical difficulties was compared to typically developing children. The children with low mathematical ability were expected to obtain lower scores and possibly also diminished growth on the three executive function tasks than typically developing children.

Next, the predictive value of executive functions was investigated using discriminant analysis. In order to do this, two types of mathematical difficulties were defined: (a) mathematical difficulties at the end of 2nd grade and (b) persistent mathematical difficulties throughout 1st and 2nd grade. It was investigated how well executive functions could predict both types of mathematical difficulties separately. The first classification was used to investigate whether executive functions could predict later mathematical difficulties: executive function measures were obtained 1.5 year to 3 months before the mathematics measure. However, approximately one-third of individuals that meet low achievement criteria at one time do not maintain low achievement over time (Vukovic & Siegel, 2010). Therefore the second classification was created in which only those children with consistent low performance on four subsequent occasions were defined as having mathematical difficulties. Thus, the advantage of the first classification was to investigate the prediction of future achievements, while the second classification targeted only children with persistent mathematical difficulties. It was investigated how well executive functions alone could predict group membership correctly. In addition, it was investigated which executive function was the best predictor, and in which early stage it was possible to predict these group classifications. Finally, it was investigated whether the inclusion of executive function measures could improve the predictions made by preparatory mathematical abilities alone. All three functions were expected to be predictors of mathematical difficulties.

Since longitudinal research considering executive functions and mathematical abilities is scarce, this study is a valuable addition to currently available literature. Especially because a distinction between persistent and single poor mathematical performance is made, this study will contribute to identifying those children who are at serious risk for developing special needs in mathematical learning, and to identifying targets of intervention for these children.

Method

Participants

At the beginning of the study, 227 children (120 boys, 107 girls) with a mean age of 6.5 years (*SD* = 4.3 months; range 5.9–7.7 years) took part. Children came from 18 classes in 10 schools. School choice was based on three criteria: (1) a low number of children not speaking Dutch at home, (2) diversity in SES (i.e. schools with high and low numbers of parents that completed less than 2 years of secondary education) and (3) use of the same mathematics teaching method. As the aim was to obtain a representative sample of children following regular education, there were no stringent exclusion criteria; however, three children were excluded because of failure to understand the task instructions (one child with Down syndrome and two refugee children with insufficient mastery of the Dutch language).

During the course of the study, fifteen more children (5.8%) dropped out, due to moving (seven children), grade retention (three children) and accelerating a grade (five children). All analyses were performed with the 209 remaining children (108 boys, 101 girls, mean age at beginning of study = 6.14 years, *SD* = 4.5 months). Parental consent was obtained for all participating children.

Two classifications were made, based on mathematical performance on four different time-points, called measurements (halfway and end of 1st grade and halfway and end of 2nd grade). The first classification into two groups was based on the test results of the latest measurement, at the end of 2nd grade. This distinction was made as closely as possible to a 25%–75% proportion of the total group of children: one group with the 25% lowest scoring children on the mathematical test (Grade 2 Low, G2L) and one group with the 75% remaining children: the typically performing group (Grade 2 Typical, G2T). Descriptive statistics of the groups are presented in Table 2.1. There was a significant association between gender and group classification, χ^2 (1) = 6.35, $p < .05$, $V = .17$, with the poor group containing more females and the normal group containing more males. This corresponds with results from other studies (e.g., Penner & Paret, 2008).

The second classification was based on the results of all four mathematical tests throughout 1st and 2nd grade. The children were classified into three different groups: a persistent very low performing (Persistent Very Low, PVL) group with test scores on each measurement below the 25th percentile (on each measurement belonging to the 25% lowest scoring children); a persistent below average performing (Persistent Below Average, PBA) group with test scores not low enough to qualify for the PVL group but always below the 50th percentile (on each measurement belonging to the 50% lowest scoring children) and a Typically Achieving (TA) group of the remaining children. Descriptive statistics of the three groups are presented in Table 2.1. The PVL group consists of 10% of the children, which corresponds with the prevalence of previous research (e.g., Dirks et al., 2008). Again, there was a similar significant association between gender and group classification, χ^2 (2) = 9.35, $p < .01$, $V = .21$.

Procedure

There were three measurements for executive functions: beginning (October) 1st grade, halfway (March) 1st grade and beginning (October) 2nd grade. All executive function tasks were computer tasks that were administered individually, with the exception of

Table 2.1 Descriptive statistics of the groups in the two classifications

Group	*N* (%)	Gender		Age in months	
		Male (%)	Female (%)	*M*	*SD*
First classification					
G2L	52 (24.9)	19 (36.5)	33 (63.5)	73.56	4.81
G2T	157 (75.1)	89 (56.7)	68 (43.3)	73.74	4.36
Second classification					
PVL	21 (10.0)	8 (38.1)	13 (61.9)	73.26	4.31
PBA	45 (21.4)	16 (35.6)	29 (64.4)	73.64	5.01
TA	143 (68.4)	84 (58.7)	59 (41.3)	73.73	4.34

Note. G2L = Grade 2 Low, G2T = Grade 2 Typical, PVL = Persistent Very Low, PBA = Persistent Below Average, TA = Typically Achieving.

the Simon Task and the Sorting Task, which the children completed in duos, each having their own laptop. Executive functions were measured in a fixed order in three 30-minute sessions at each measurement. Tests were administered by trained (under)graduate students, as was preparatory mathematical ability, which was measured individually at the end (June) of kindergarten. Mathematical abilities were measured four times: halfway (January) and end (June) of 1st and 2nd grade; these tests were administered group wise by the teacher.

Instruments

Mathematical abilities

Preparatory mathematical abilities. Preparatory mathematical abilities were measured at the end of kindergarten (June) with the Early Numeracy Test (ENT; Van Luit, Van de Rijt, & Pennings, 1994). The ENT is a 40-item test for children between the ages of four and seven year old. This test assesses counting skills and math prerequisites. The test consists of eight parts: concepts of comparison, classification, correspondence, seriation, using numerals, synchronized and shortened counting, resultative counting and general understanding of number. Each component has 5 items. The reliability coefficient is .94. The raw score of a child is converted to a scaled score.

Mathematical abilities. Mathematical abilities in 1st and 2nd grade were measured by four versions (1st grade (halfway and end) and 2nd grade (halfway and end) of the criterion-based Cito Mathematics Test 2008 (CMT; Janssen, Scheltens, & Kraemer, 2005a). These are national Dutch tests with good psychometric properties that are commonly used in Dutch schools to monitor the progress of primary school children. Each test contains 50 (grade 1), 52 (halfway grade 2) or 54 (end grade 2) items that are administered on two separate days. In grades 1 and 2, five main domains are covered; (1) numbers and number relations, covering the structure of the number line and relations between numbers, (2) simple addition and subtraction, (3) simple multiplication and division, (4) complex maths applications, often involving multiple mathematical manipulations and (5) measuring (e.g., weight and length). Raw scores are converted into competence scores that increase throughout primary school, enabling the comparison of results of different versions (Janssen, Scheltens, & Kraemer, 2005b; 2005c). The reliability coefficients of the four versions are respectively .92, .91, .93 and .93 (Janssen, Verhelst, Engelen, & Scheltens, 2010).

Executive functions

Executive functions investigations should contain multiple tests per executive function (Miyake et al., 2000), especially when the reliability of the tasks is unknown. Therefore, inhibition and WM were measured with three computer tasks and shifting was measured with two computer tasks. The instruction of all tasks was standardized. There was a practice item before each task in which feedback was provided. The shifting and inhibition tasks contained one or two control tasks and one executive function task. The total score on these tasks was the difference between the response time on the executive function task and the (mean) response time on the control tasks. For the WM tasks, the total score was the total number of correct responses on that task.

Shifting: Sorting Task. In this task, based on the inhibition task of Zelazo, Müller, Frye, and Marcovitch (2003), the children had to alternate between two sorting rules: according to color and according to shape. The task was presented as a game in which a dog who likes blue and a frog who likes stars were introduced to the child. The child had to give the animal the stimuli that it liked, while throwing away stimuli the animal did not like. The task contained two control blocks and a shifting block. In each block, the stimuli were 40 orange and blue stars and squares. In the first control task, only the dog, that loved blue things but hated orange, was introduced. When a blue picture appeared the children had to give the picture to the dog, which was shown on the lower left side of the screen. When an orange picture appeared the children had to throw the picture in the waste bin, which was shown on the lower right side of the screen. In the second control task, only the frog who loved star figures but hated squares, was introduced.

When a picture of a star appeared the children had to give the picture to the frog. When a picture of a square appeared the children had to throw the picture in the waste bin. The shifting task was a mixed block in which sometimes the dog and sometimes the frog appeared; the same 40 stimuli were shown again. The children had to give the picture to the animal or throw the picture in the waste bin. During the three tasks, after 700 ms a stimulus appeared. The children 'gave' the picture to the animal by pressing the A button on the left side and the child 'threw it away' by pressing the L button on the right side. No feedback was provided.

Shifting: Animal Shifting. In this task, based on the 'Symbol Shifting'-task (Van der Sluis et al., 2007) the children had to name stimuli that were presented on the computer screen as quickly as possible. The eight stimuli consisted of four animal species (bird, fish, dog, and cat) and four fruit species (banana, pear, cherry, and strawberry). In the control task, 40 stimuli were presented one at a time. In the shifting task, two stimuli were presented simultaneously on the same screen. The children had to name only one of the stimuli, depending on the color of the screen background: the fruit when it was yellow, the animal when it was purple. Again, 40 stimuli were presented. All stimuli were preceded by a 700 ms fixation cross.

Inhibition: Animal Stroop. Inhibition ability was measured by the 'Animal Stroop'-task (Wright, Waterman, Prescott, & Murdoch-Eaton, 2003). In this task, animals were presented that are composed of the body of one animal and the head of another. The child had to name the animal body rather than the more salient animal head. The four stimuli, sheep, duck, cow, and pig, were presented one at a time, preceded by a 400 ms fixation cross. In the facilitation task, which contained 48 items, the children were asked to name the presented stimuli as fast as possible. The stimuli remained on the screen until the child responded. The control task consisted of bodies of the four stimuli presented with a human head (48 items). The inhibition task consisted of bodies of the four stimuli presented with another animals head (48 items). The children were asked to name the bodies of the animals as fast as possible. In both tasks the test assistant pushed the space bar at the time of the call. After this the assistant pushed the 'g' key when the answer was correct and the 'f' key when the answer was incorrect.

Inhibition: Simon Task. Inhibition ability was also measured by the 'Simon Task', based on the original Simon Task (Simon, 1969). The Simon effect can be elicited with tasks where stimuli are presented at different locations on a screen, while this spatial aspect must be ignored. The task consisted of two conditions: one control task and one inhibition task. In the inhibition task half of the items were congruent and half of the items were incongruent. The children had to press the A button when a picture of a mouse appeared on the screen and press the L button when a picture of a dragon appeared on the screen. A cage appeared when the child pushed the right button. During the control task the 40 stimuli appeared in the centre of the screen. During the inhibition task the stimuli appeared on one side of the screen. The mouse could appear on the left side (congruent) or the right side (incongruent). The dragon could appear on the left side (incongruent) or the right side (congruent). All stimuli were preceded by a 500 ms fixation cross.

Inhibition: Local Global. Inhibition ability was also measured by the 'Local Global'-task. In this task identical small geometrical shapes (circle, triangle, square) that together constituted a larger, different geometrical shape were presented. Sometimes the large, global shape had to be named, sometimes the small, local shapes. In general, people show a global preference: reaction times are faster when the large image has to be named rather than the local shapes (Navon, 1977). The task consisted of three conditions: one control task and two inhibition tasks. In the control task, the children were asked to name 48 single, small geometrical shapes. The inhibition tasks each consisted of 48 larger stimuli that were constructed from the stimuli presented in the control task. All stimuli in these blocks were incongruent: the shape of the larger image was always different from the elements from which it was built. In the first inhibition task, the children had to name the large stimulus, while in the second inhibition task the children had to name the small image. The stimuli were preceded by a 400 ms fixation cross.

Working memory: Keep Track. A computerized version of the 'Keep Track'-task (Miyake et al., 2000; Van der Sluis et al., 2007) was administered. During the task pictures belonging to five categories, were presented in sets of ten: fruit (strawberry, banana, pear, cherry), animals (dog, cat, bird, fish), shapes (circle, square, triangle, heart), toys (scooter, blocks, teddy bear, car), and sky (sun, moon, stars, cloud). The task consisted of eight series with four different difficulty levels. Prior to a series the children were asked to pay special attention to one or more categories. The number of categories increased after two series, starting with one category and ending with four. First, the children were asked to name each presented picture. Second, the children were asked to name the last presented picture of the category to which they had to pay special attention. During the task a white picture at the bottom of the screen helped the children remember the category of attention. In each series the children could gave one, two, three, or four correct answers. The sum of the correct answers was the final score.

Working memory: Odd One Out. An adaptation of the Dutch version of Odd One Out from the Automated Updating Assessment test battery WM (Alloway, 2007) was administered. Three boxes with shapes were presented next to each other. One of the shapes was different from the other two. The child pointed at the different shape. Then three new shapes appeared. At the end of each trial three empty boxes appeared and the child had to point at the locations of the previously-shown different shapes in the same order in which they appeared. An answer was considered correct if each location was recalled correctly in the right order. The task started with only one item; after three correct answers of the same length the sequence increased by one. When two mistakes were made in trials of the same length, the task was discontinued. The number of correct responses was used as a final score.

Working memory: Digit Span Backwards. This task was also adapted from the Automated Updating Assessment (Alloway, 2007). The children were asked to repeat a recorded digits sequence backwards. The task started with two digits. After completing three right items of a certain length, an extra digit was added. After completing two wrong items in the same series the task was ended. The number of trials recalled correctly was used as a final score.

Outlier analysis

The scores on the shifting and inhibition tasks represent response times. Response time can only be considered a valid score if the number of errors is limited (Huizinga, Dolan, & Van der Molen, 2006; Van der Sluis et al., 2007). The response time scores on the shifting and inhibition tasks were removed if the accuracy on the task was less than 55% correct, a standard based on the study of Huizinga et al. (2006). Therefore, twelve Animal Shifting scores (seven from the first measurement, four from the second measurement and one from the third measurement), one Simon Task score (second measurement) and two Sorting Task scores (one from he first measurement and one from the second measurement) were removed.

Results

The overall mean scores and the mean scores of the five groups on the eight executive function tasks on the three measurements are presented in Table 2.2. For further analyses, shifting and inhibition tasks scores were recoded, so correlations are always positive in the expected direction. Two different statistical analyses were carried out.

All analyses were conducted using an alpha of .05. First, the development of the three executive functions and group differences in this development were investigated. For each task two ANOVAs for repeated measures were carried out to examine whether the means on the tasks indeed differed between the measurements. In eight ANOVAs the two groups of the first classification were added as independent variable and in the other eight ANOVAs the three groups of the second classification were added as independent variable. The Mauchly's test of sphericity was used to test the assumption of sphericity. In case of the Animal Stroop and Keep Track this assumption was violated. Therefore, a Greenhouse-Geisser correction was conducted on four of the analyses. Post hoc analyses with a Bonferroni adjustment were carried out correcting for an experiment-wise error rate. The results of the repeated measures ANOVAs are described separately for each executive function.

Shifting

In each of the two classifications no main effect of group was found. Only the analyses on Animal Shifting showed a main effect of time. There was a significant development in the expected direction between all the measurements for both the first classification (F (2,414) = 25.38, $p < .01$, $\eta^2 = .11$) and the second classification (F (2,412) = 22.78, $p < .01$, $\eta^2 = .10$). In none of the analyses a significant interaction effect between time and group was found.

Inhibition

In each of the two classifications no main effect of time or group was found for Local Global and the Simon Task. Animal Stroop scores increased significantly between the first and the second measurement, but not between the second and the third measurement. This main effect of time was found for both the first classification (F (1.94,400.81) = 65.75, $p < .01$, $\eta^2 = .24$) and the second classification (F (1.94,398.87) = 44.56, $p < .01$, $\eta^2 = .18$). Furthermore, these analyses showed a main effect of group. Group differences were found between the two groups in the first classification (F (1,207) = 5.65, $p = .02$, $\eta^2 = .03$) and all three groups in the second classification (F (2,206) = 4.16, $p = .02$, $\eta^2 = .04$). The group differences were consistent with the expectations: children with low mathematical ability obtained lower scores than typically developing children. In none of the analyses a significant interaction effect between time and group was found.

Table 2.2 Descriptive statistics of the five groups on the eight executive tasks on the three measurements

			Total		First classification				Second classification					
					G2L		G2T		PVL		PBA		TA	
Function	Task	ME	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Shifting	Sorting Task*	1	0.43	0.14	0.42	0.13	0.43	0.14	0.38	0.09	0.42	0.13	0.44	0.15
		2	0.42	0.16	0.41	0.17	0.13	0.16	0.39	0.19	0.41	0.16	0.44	0.16
		3	0.40	0.15	0.41	0.11	0.39	0.16	0.42	0.13	0.36	0.12	0.41	0.15
	Animal Shifting*	1	0.38	0.11	0.37	0.10	0.38	0.11	0.38	0.08	0.36	0.09	0.38	0.12
		2	0.34	0.11	0.33	0.11	0.34	0.11	0.32	0.09	0.33	0.12	0.34	0.11
		3	0.30	0.11	0.31	0.11	0.30	0.11	0.29	0.09	0.30	0.11	0.31	0.11
Inhibition	Animal Stroop*	1	0.24	0.09	0.22	0.08	0.25	0.09	0.21	0.09	0.23	0.09	0.25	0.09
		2	0.17	0.08	0.16	0.08	0.17	0.08	0.15	0.07	0.16	0.08	0.18	0.08
		3	0.17	0.07	0.15	0.08	0.17	0.07	0.16	0.08	0.15	0.08	0.17	0.07
	Simon Task*	1	0.41	0.14	0.44	0.14	0.40	0.14	0.45	0.11	0.43	0.15	0.39	0.14
		2	0.40	0.17	0.41	0.13	0.40	0.18	0.38	0.15	0.44	0.23	0.40	0.15
		3	0.39	0.15	0.41	0.18	0.38	0.14	0.44	0.19	0.40	0.16	0.38	0.15
	Local Global*	1	0.20	0.10	0.19	0.10	0.20	0.10	0.16	0.09	0.19	0.09	0.20	0.10
		2	0.19	0.10	0.18	0.09	0.19	0.10	0.19	0.09	0.17	0.08	0.20	0.10
		3	0.19	0.10	0.19	0.10	0.19	0.10	0.20	0.11	0.18	0.09	0.19	0.11
WM	Keep Track	1	11.73	3.03	10.40	2.7	12.17	3.00	9.14	2.63	11.60	2.77	12.15	2.98
		2	12.97	2.70	11.87	2.8	13.33	2.60	11.48	2.91	11.67	2.67	13.59	2.46
		3	13.92	2.87	12.40	2.9	14.43	2.67	11.71	2.63	12.73	2.82	14.62	2.64
	Odd One Out	1	6.79	2.44	6.10	2.6	7.02	2.36	5.86	2.52	6.11	2.49	7.14	2.35
		2	7.75	2.65	7.25	2.3	7.92	2.74	6.95	2.18	6.89	2.51	8.14	2.67
		3	8.40	2.63	7.35	2.3	8.75	2.64	6.81	1.94	7.51	2.52	8.91	2.60
	DSB	1	3.76	1.68	3.23	1.5	3.93	1.71	3.19	1.25	3.53	1.53	3.91	1.76
		2	4.67	1.55	3.98	1.3	4.89	1.60	4.05	1.02	4.51	1.24	4.80	1.68
		3	4.97	1.57	4.79	1.3	5.03	1.65	4.76	1.38	4.56	1.24	5.13	1.67

Note. G2L = Grade 2 Low, G2T = Grade 2 Typical, PVL = Persistent Very Low, PBA = Persistent Below Average, TA = Typically Achieving, ME = Measurement, * = The lower the score, the better the shifting/inhibition ability. WM = Working Memory, DSB = Digit Span Backwards.

Working memory

The analyses showed a main effect of time in the expected direction on each task on both classifications (see Table 2.3). The significant development for Odd One Out was only found between the first and the second measurement in both classifications. The same result was found for Digit Span Backward for the second classification. Furthermore, a main effect of group, consistent to the expectations, was found on each task within both classifications (see Table 2.3). Children with low mathematical ability obtained lower scores than typically developing children. On Odd One Out and Keep Track post hoc analyses revealed that in the second classification no difference was found between the PVL and the PBA group. A significant interaction effect was found for Keep Track on the second classification (F (3.84,397.90) = 3.02, p = .02, η^2 = .03). The PVL group developed faster than the PBA group between the first and the second measurement.

Second, eight discriminant analyses (four for each classification) were carried out to investigate the overall accuracy of the predicted classifications in the groups based on the executive functioning scores and the score for preparatory mathematical abilities. The sensitivity of the predictors was described: the percentage of children in the observed groups that were predicted correctly. Four discriminant analyses were conducted to examine how well executive functions, in addition to preparatory mathematical abilities, could predict group membership in the 1st classification. The results of these analyses are displayed in Table 2.4. In the first analysis, the executive functions tasks were used to investigate which executive function task predicted group membership best. Because the number of predicted variables should be smaller than 1:20 (Stevens, 1986), the mean of the three measurements was taken as a score on the

Table 2.3 Results of repeated measures ANOVAs on three working memory tasks

	Difference in time				Difference between groups			
Task	F	df	p	η^2	F	df	p	η^2
					First classification			
Keep Track	37.16	1.91,394.36	< .01	.15	26.95	1,207	< .01	.12
Odd One Out	19.21	2,414	< .01	.09	11.71	1,207	< .01	.05
DSB	43.20	2,414	< .01	.17	10.56	1,207	< .01	.05
					Second classification			
Keep Track	26.64	1.92,395.63	< .01	.12	20.85	2,206	< .01	.17
Odd One Out	12.26	2,412	< .01	.06	12.79	2,206	< .01	.11
DSB	30.28	2,412	< .01	.13	3.79	2,206	.02	.04

Note. DSB = Digit Span Backwards.

executive function tasks. The overall Wilks's Lambda was significant, $\Lambda = .88$, χ^2 (8) = 24.95, $p < .01$, indicating that the eight executive function tasks could distinguish the low and the typical achievers in grade 2 (G2L and G2T). 62.7% of the children were classified correctly into their group (see Table 2.4). The standardized canonical discriminant function coefficients were the highest for the three WM tasks (see Table 2.5), which means that the three WM tasks demonstrated the strongest relationship with the general mathematical achievement. Therefore, three other discriminant analyses were conducted to investigate the predictive value of the WM tasks only, and the predictive value of WM over the ENT. First, the predictive value of only WM and only the ENT-score was examined. The overall Wilks's Lambda was significant for both WM, $\Lambda = .92$, χ^2 (3) = 17.89, $p < .01$: 62.7% classified correctly, and the ENT, $\Lambda = .86$, χ^2 (1) = 30.43, $p < .01$: 67% classified correctly (see Table 2.5). Second, the predictive value of the ENT-score together with the scores on the three WM tasks on the first measurement was examined. The overall Wilks's Lambda was significant ($\Lambda = .84$, χ^2 (4) = 36.63, $p < .01$). 67.9% of the children were classified correctly. The predictive value of the individual ENT-score was lower than the predictive value of the WM tasks only, concerning the 25% lowest performing children. The WM tasks did not have an additional value besides just the ENT task.

A similar procedure as described above was carried out for the second classification: the groups with persistent very low, below average, or typical mathematical performance during 1st and 2nd grade (from 6 to 8 years). Again, the mean of the three measurements was taken as score on the executive function tasks in the first analysis to investigate which executive function task predicted group membership best. The overall Wilks's Lambda was significant, $\Lambda = -.16$, χ^2 (9) = 36.46, $p < .01$, indicating that the eight executive function tasks differentiated between the three groups. 55.7% were classified

Table 2.4 Results of discriminant analyses; percentages of children classified correctly

	First classification		Second classification			
Predictors	G2L	G2T	PVL	PVL as PBA	PBA	TA
Mean EF	65.4	61.8	71.4	23.8	40.0	58.3
WM	63.5	62.4	57.1	28.6	28.9	50.3
ENT	76.9	63.5	57.1	33.3	26.7	67.1
ENT and WM	75.0	65.6	66.7	28.6	40.0	59.4

Note. G2L = Grade 2 Low, G2T = Grade 2 Typical, PVL = Persistent Very Low, PBA = Persistent Below Average, TA = Typically Achieving, Mean EF = Executive Functions, WM = Working Memory, ENT = Early Numeracy Test.

Table 2.5 Results of discriminant analyses on the mean of the eight executive function tasks: standardized canonical discriminant function coefficients

Function	Task	1st classification	2nd classification
		Standardized canonical discriminant function coefficients	Standardized canonical discriminant function coefficients
Shifting	Sorting Task	-.19	-.28
	Animal Shifting	-.12	-.04
Inhibition	Animal Stroop	-.46	-.42
	Simon Task	.33	.33
	Local Global	-.08	-.30
Working memory	Keep Track	.72	.68
	Odd One Out	.46	.44
	DSB	.51	.32

Note. DSB = Digit Span Backwards.

correctly (see Table 2.4). From Table 2.5 it can be seen that in general the three WM tasks demonstrated the strongest relationship with the mathematical achievement.

Therefore, three other discriminant analyses were conducted to investigate the predictive value of the WM tasks only, and the predictive value of WM over the ENT. First, the predictive value of only WM and only the ENT-score was examined. The overall Wilks's Lambda was significant for both WM, Λ = -.10, χ^2 (4) = 21.63, $p < .01$: 46.4% classified correctly, and the ENT, Λ = .81, χ^2 (2) = 41.88, $p < .01$: 57.4% classified correctly (see Table 2.5). Moreover, Table 2.4 also shows the percentage of the PVL group that was classified correctly (WM: 57.1%, ENT: 57.1%) and classified as the PBA group (WM: 28.6%, ENT: 33.3%). Together 85.7% of the children in the PVL group were classified into one of the risk groups (PVL or PBA group) based on the WM-scores. Of the children from the PVL group a total of 90.4% was classified into one of the risk-groups (PVL or PBA) based on the ENT score. Second, the predictive value of the ENT-score together with the scores on the three WM tasks on the first measurement was examined. The overall Wilks's Lambda was significant (Λ = -.21, χ^2 (5) = 50.02, $p < .01$). 56% of the children were classified correctly. Of the PVL group a total of 95.3% was classified into one of the at-risk groups (PVL or PBA). The predictive value of the individual ENT-score was comparable to the predictive value of the WM tasks only, concerning the (very) low performing children at risk for developing mathematical difficulties. The ENT-score in combination with the WM scores gave the best prediction of which children are at risk for mathematical difficulties (PVL or PBA; 95.3%).

Conclusion and discussion

The aim of this study was to investigate whether executive functions are a good early predictor of later mathematical difficulties, both persistent and based on one single test score, compared to the predictive value of preparatory mathematical abilities. Therefore, two classifications were made. First, children were grouped into two groups based on their low or typically math performance at the end of 2nd grade (G2L and G2T). Second, the same children were grouped into three groups based on their mathematical performance throughout 1st and 2nd grade: persistent very low performers (PVL), persistent below average performers (PBA) and normal, high, or fluctuating performers (Typically Achievers, TA). The PVL and PBA children are those children that need special attention, because they are at risk for developing mathematical difficulties (PBA) or already show disabilities in their mathematical performance (PVL). The advantage of the first classification was to investigate the prediction of future achievements, while the second classification targeted only children with persistent low scores in their mathematical performance.

The development of executive functions in these groups was investigated to examine whether there were differences between the groups and between the three measurements of executive functions measurements. In contrast with the expectations that children with poor mathematical ability perform worse on all three executive functions, in the present study only on the WM tasks differences in development and between groups were found. The low performing children in grade 2 (G2L) and the persistent very low (PVL) or persistent below average (PBA) performing children in grade 1 and 2 obtained significant lower scores on WM than typically performing children. Furthermore, the results of the discriminant analyses show WM ability as the executive function that predicts mathematical difficulties best. These findings for the WM tasks correspond with previous studies in which a relationship is found between WM, or the related concept of updating, and mathematical difficulties (e.g., Bull et al., 2008; Mabbott & Bisanz, 2008; Kroesbergen et al., 2009; Passolunghi et al., 2007; Schuchardt et al., 2008; Vuvokic & Siegel, 2010). WM ability is believed to be necessary because information from long term memory must be stored and manipulated during mathematical problem solving. Children with lower WM skills are expected to experience difficulties in storing and manipulating information during mathematical problem solving (Andersson, 2008).

No unequivocal results were found for the shifting and inhibition tasks, concerning the development and group differences on the five tasks. In some studies a relation between shifting ability and mathematical achievement was found (e.g., Bull et al., 2008). However, this relationship was not confirmed by others (Espy et al., 2004; Van der Sluis et al., 2004). Except for the Animal Stroop task, the groups did not differ in their development of shifting and inhibition in the present study, which seems to indicate that these two executive functions do not play a crucial role in mathematical abilities. The results of the discriminant analyses revealed a similar pattern. In comparison to WM ability, shifting and inhibition did not contribute to the correct classification of children at risk for mathematical difficulties. According to several studies (Andersson, 2008; Van der Sluis et al., 2007), shifting ability is believed to be involved in mathematical performance by supporting alternation between strategies and sub-solutions in multi-step mathematics problems and inhibition ability is believed to be necessary for active suppression of immature strategies and task-irrelevant information during mathematical problem solving (Bull et al., 2008; St Clair-Thompson & Gathercole, 2006). However, the complexity of mathematical tasks in 1st and 2nd grade is relatively simple, as not all tasks require multi-step solutions or contain irrelevant information. This could mean that the role of shifting and inhibition in mathematical tasks increases when the complexity of the tasks and the required knowledge increases. Further research is necessary to investigate the role of these two executive functions in older children.

For practical relevance of the present study a comparison was made between the predictive value of WM ability and the predictive value of preparatory mathematical abilities. The present study confirms the predictive value of preparatory mathematical abilities in identifying children at risk for developing mathematical difficulties (Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Locuniak & Jordan, 2008; Morgan et al., 2009; Stock et al., 2010), because the ENT identified 76.9% of the G2L group in the first classification and 57.1% of the PVL and PBA group in 1st and 2nd grade. With the results of the present study, the importance of WM ability is added to this knowledge, especially for persistent mathematical difficulties in 1st and 2nd grade. The three WM tasks at the beginning of 1st grade predicted the same percentage (57.1%) of children with mathematical difficulties through 1st and 2nd grade as preparatory mathematical ability did. This confirms findings from a previous study (Welsh et al., 2010). Together, the ENT and the WM tasks predicted the children with mathematical ability even better (66.7%). Furthermore, almost all children (95.3%) with persistent mathematical difficulties were identified as at risk for developing problems in mathematical performance on basis of these two factors.

On a practical level, this implies that many children at risk for developing mathematical difficulties can be identified at the beginning of 1st grade through a test battery with WM tasks, such as the Automated Working Memory Assessment (AWMA; Alloway, 2007), as supplement to a diagnostic instrument that measures the preparatory mathematical abilities of these children. Clinicians are encouraged to take WM ability into account when assessing math learning disabilities. Apart from facilitating the identification of at-risk children, this will also give useful insights in possible gaps in the skills of these children.

However, in the first classification the WM tasks had no additional predictive value. Because of the distinction that was made between difficulties based on one test score (first classification) and persistent mathematical difficulties based on four test scores (second classification), this seems to indicate that the role of WM ability increases when it concerns persistent mathematical difficulties instead of difficulties based on one single measurement. Besides, the children were older at this last measurement so this could entail that the role of WM in mathematics decreases when children become older or that the predictive value of WM is less strong when the prediction is carried out one and a half year before the measurement of mathematical abilities. Further research is necessary to confirm this statement and to investigate the specific possibilities for using WM ability for identifying children at risk for mathematical learning disabilities.

In the last decade more attention has been paid to stimulating preparatory mathematical abilities in children performing below average (Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005; Van de Rijt & Van Luit, 1998; Van Luit & Schopman, 2000). This study confirms the practical importance of studying the possibility of stimulating preparatory mathematical abilities. Moreover, this study emphasizes the importance of also stimulating other skills like WM ability to prepare preschool children for formal mathematic instruction in 1st and 2nd grade. Research has shown the possibility of stimulating working memory in older children (Holmes, Gathercole, & Dunning, 2009), but limited studies are carried out focusing on training working memory in kindergarten and 1st grade. Therefore, research on stimulating different components of working memory in young children should be carried out.

To summarize, this study confirms the practical importance of using the concept of working memory in screening children at risk for math learning disabilities and assist these children by prevention programs with a focus on preparatory mathematical abilities and working memory. However, the results of the current study should be interpreted in the light of several limitations. First, in previous studies separate tasks were combined into a common score on basis of factor analysis (Fournier-Vicente, Larigauderie, & Gaonach, 2008; Huizinga et al., 2006; Miyake et al., 2000; St Clair-

Thompson & Gathercole, 2006; Van der Sluis et al., 2007). In this study, the interpretation of the observed differences is only possible on task level. Therefore, despite the use of control tasks, the task impurity problem (e.g., Miyake et al., 2000) raises the question if the tasks are true representations of the underlying executive functions. A second limitation is the use of the same tasks at three measurements. An executive function can be measured best when a task is new to the child, regarding the content as well as the form, because the tasks tend to suffer from relatively low test-retest reliability (Rabbitt, 1997). Efforts were made to minimize this problem by keeping the measurements six months apart. Despite the several limitations, this study indicates that it may be promising to use working memory ability in early identification of children at risk for mathematical learning difficulties.

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Explaining numeracy development in weak performing kindergartners

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Abstract

As children with inadequate early numeracy skills are at risk for developing mathematical learning difficulties at a later stage, it is interesting to gain better insight into precursors of early numeracy in children within this interest group. Therefore, in the present study, visual and verbal working memory, non-symbolic and symbolic comparison skills, and specific math-related language is used to explain early numeracy performance and development of weak performing children throughout kindergarten. The early numeracy ability of both weak performers (WP) and typically performers (TP) was measured at four time points during two years of kindergarten, in order to compare the growth rates. Results show a significant faster development of early numeracy in the WP children. The development of WP children's numeracy was influenced by verbal working memory, symbolic comparison skills, and math language, while visual working memory, non-symbolic comparison skills, and again math language showed an effect on the initial early numeracy level of those children.

Introduction

Starting to learn basic mathematical calculations in first grade requires particular prerequisite skills, such as (verbal) counting, knowing the number symbols, recognizing quantities, discerning number patterns, comparing numerical magnitudes, and estimating quantities (Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Fuchs et al., 2010; Gersten, Jordan, & Flojo, 2005; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). This general understanding of numbers is defined as "early numeracy skills" (Passolunghi & Lanfranchi, 2012), not to be confused with number sense, which is pre-verbal and innate (e.g., Butterworth, 2005). Findings from longitudinal studies show the importance of early numeracy competence for setting children's learning trajectories in primary school mathematics (e.g., Jordan, Glutting, & Ramineni, 2010; Jordan, Kaplan, Ramineni, & Locuniak, 2009).

For most children, learning to master these early numeracy skills is a natural process that is guided by (in)formal learning which occurs in the home and preschool environment (e.g., Ginsburg, Lee, & Boyd, 2008). Not all children, however, develop this knowledge spontaneously. Research shows a reciprocal relationship between math interest and math development in preschool (Fisher, Dobbs-Oates, Doctoroff, & Arnold, 2012). As a result, by the age of five, some children already trail behind in their early numeracy knowledge, and are not able to catch up with their typically developing peers during primary school when it comes to mathematical knowledge (Stock, Desoete, & Roeyers, 2010; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011) and fluency (Locuniak & Jordan, 2008). In other words, it is possible to effectively predict which kindergartners are at risk for math learning difficulties based on early numeracy scores obtained during kindergarten (Mazzocco & Thompson, 2005).

Longitudinal research on typically achieving children has documented that early numeracy in kindergarten and math skills in the beginning of primary school can be identified by several precursors, often divided into domain-specific and domain-general precursors (Passolunghi & Lanfranchi, 2012; Welsh, Nix, Blair, Bierman, & Nelson, 2010). Research on precursors in early numeracy focusing specifically on children with insufficient skills, however, is rather scarce. Since children with inadequate early numeracy skills are at risk for developing mathematical learning difficulties at a later stage, it is interesting to gain better insight into the precursors of early numeracy in children within this interest group. Therefore, in the present study, three different precursors (working memory, comparison skills, and math-related language) will be used to explain early numeracy performance and development throughout kindergarten, before the point where children start formal mathematical education in first grade. This study builds on the current idea that early precursors in math learning difficulties can be addressed as key components in remedial programs and interventions, preventing children from falling further behind (e.g., DiPerna, Lei, & Reid, 2007; Dowker & Sigley, 2010).

Working memory

As one of the most important domain-general precursors of early numeracy (Passolunghi & Lanfranchi, 2012; Passolunghi & Mammarella, 2012; Passolunghi, Vercelloni, & Schadee, 2007), working memory is considered important for early mathematical performance because incoming information must be stored and manipulated during the dissolving of mathematical tasks (e.g., De Smedt et al., 2009; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Swanson, 2011). Studies examining the relationship between working memory and early numeracy skills in kindergarten (e.g., Espy et al., 2004; Kroesbergen, Van de Rijt, & Van Luit, 2007; Kyttälä, Aunio, & Hautamäki, 2009) specifically show the importance of identifying working memory characteristics in the early development of mathematical cognition (Klein & Bisanz, 2000). Even at a young age, children constantly need to revise their stored information during the execution of early numeracy tasks. Welsh and colleagues (2010), for example, conclude that working memory, and other domain-general cognitive skills such as attention, make unique contributions to the prediction of kindergarten numeracy achievement.

In research on working memory, the model proposed by Baddeley and Hitch (1974) has proven to be useful. In this model, the term working memory is defined as the ability to store and manipulate information simultaneously (e.g., Baddeley, 1986; Baddeley & Hitch, 1974). Within working memory, a distinction can be made between verbal and visual working memory (Alloway, Gathercole, & Pickering, 2006). This basic modular structure of working memory has proven to be stable and assessable by the age of four (Alloway, Gathercole, Kirkwood, & Elliott, 2008; Alloway, Gathercole, Willis, & Adams, 2004; Gathercole, Pickering, Ambride, & Wearing, 2004).

Both visual and verbal working memory types were repeatedly related to math achievement and development (e.g., Andersson & Lyxell, 2007; De Smedt et al., 2009; Krajewski & Schneider, 2009a). However, according to the review by Raghubar, Barnes, and Hecht (2010), no consensus can be reached about which component contributes most to math development. Where some studies show verbal working memory (i.e., the phonological loop) to be correlated to children's performance in prerequisites in mathematics (Noël, 2009), other studies verify that visual-spatial working memory is important (e.g., Krajewski & Schneider, 2009a). Yet, findings from studies on children of all ages suggest that visual working memory may be recruited for the learning and application of new mathematical skills and concepts, whereas verbal working memory may come into play after a math skill has been learned (Raghubar et al., 2010). For example, the results of Kyttälä, Aunio, Lehto, Van Luit, and Hautamäki (2003) suggest that verbal working memory skills may be more generic in terms of supporting mathematical skills during primary school, whereas visuospatial working memory may be more specific to early mathematical learning. In addition, Bisanz, Sherman, Rasmussen, and Ho (2005) found that visual spatial working memory was the best predictor of early math performance in kindergarten, but no longer in first grade. In the literature, this phenomenon is explained by the mental model hypothesis that has been applied to explain how visuospatial memory resources are linked to mathematical learning and performance (e.g., Huttenlocher, Jordan, & Levine, 1994).

Knowledge of the contribution of the two working memory components to early numeracy in children with math difficulties is limited, because understanding of which aspects of working memory are deficient in children with math difficulties is obscured by the lack of precise knowledge of the particular strategies and processes that the child brings to bear on working memory tasks (possibly as a function of age and language) and by the lack of any theory that links these working memory processes to particular aspects of mathematical learning and performance (Raghubar et al., 2010). Nevertheless, Swanson and Jerman (2006) stated that limitations in verbal working memory characterize children with math difficulties. This is confirmed by another study (Wilson & Swanson, 2001), showing verbal working memory as a better predictor of mathematical computation than visuospatial working memory in this interest group. Controversially, McLean and Hitch (1999) conclude that visual-spatial aspects of working memory are important factors in poor early mathematics.

Comparison skills

The second precursor included in the present study is the ability to discriminate between magnitudes. It is assumed that a distinction can be made between symbolic (i.e., Arabic symbols) and non-symbolic (i.e., magnitudes) comparison skills (Desoete et al., 2012), which are interrelated (Gilmore, McCarthy, & Spelke, 2010). This distinction is based on the triple code model of Dehaene (1992; 2001), which distinguishes three different types (so-called codes) of number representations: the analog magnitude code (semantic knowledge about the proximity and relative size of quantities), the auditory verbal code (the ability to enumerate the counting row), and the visual code (Arabic representations). Dehaene (2001) hypothesized that all children are born with a system for non-symbolic quantity representation and that this can be measured as early as the first months of life. This suggests that children have an innate understanding of non-symbolic magnitudes (Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004). This statement is confirmed by studies which show that preschoolers are capable of comparing and adding large sets of elements without counting (e.g., Barth, La Mont, Lipton, & Spelke, 2005). During early childhood, symbolic knowledge develops based on increasing experience with number words (verbal code) and number symbols (visual code). Eventually, these new symbolic skills are gradually integrated with existing nonverbal knowledge, resulting in more complex cognitive representations in which number symbols and words are connected to quantity representations (Dehaene, 2001; Krajewski & Schneider, 2009b; Mundy & Gilmore, 2009; Mussolin, Mejias, & Noël, 2010).

Whether non-symbolic or symbolic skills are more important for early numeracy and math development is still a subject of discussion. One view, emphasizing the importance of non-symbolic skills, states that non-symbolic skills provide meaning to number words and number symbols which are needed in all math tasks. Non-symbolic understandings of magnitude form a necessary precondition for learning to associate a perceived number of objects with symbolic number words or number symbols (Von Aster, Schweiter, & Zulauf, 2007). There are several correlational studies that show quantity discrimination in relation to an understanding of mathematical operations (Desoete & Grégoire, 2006; Gersten et al., 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006). Furthermore, relationships were found between non-symbolic skills and math performance in children of five to eight years old (Desoete et al., 2012; Gilmore et al., 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011), indicating non-symbolic skills as a precondition for higher order mathematical abilities.

In contrast, another view suggests that the symbolic numerical skills of children might be more important than the previously developed quantitative abilities. Within this view, it is stated that non-symbolic skills seemed to play a subordinate role in learning math in contrast to the important role of symbolic skills (LeFevre et al., 2010). Moreover, several studies showed that symbolic skills predict math performance in children aged 6 to 8, and that an effect of non-symbolic skills on math performance was mediated by symbolic skills (Holloway & Ansari, 2009). For children with mathematical disabilities specifically, difficulties were found on comparing Arabic number symbols, but not on comparing dot collections (Rousselle & Noël, 2007), indicating that these children are only impaired in accessing number magnitude from symbols rather than in processing numerosity per se. Also Iuculano, Tang, Hall, and Butterworth (2008) conclude that low numeracy is not related to a poor grasp of numerosities, but rather to a poor understanding of the number symbols.

Specific math language

One precursor that is less studied in early numeracy is the ability to know and understand math-related language, in spite of Lansdell's (1999) proposal that the introduction of this "new" terminology is an important part of the teaching of early mathematical concepts. Some research has indeed indicated that linguistic ability or specific math language may be related to early numeracy skills (Hauser, Chomsky, & Fitch, 2002). It has been shown that some children experience particular difficulties in comprehending the language of mathematics (Ginsburg, 1972; Schleppegrell, 2010). So called math-related language, including math-related concepts such as "more," "less," "higher," and "lower," might facilitate the use of numerical concepts (Gelman & Butterworth, 2005; Halberda, Taing, & Lidz, 2008). Educational research shows the impact of teachers' use of this specific language (Boonen, Kolkman, & Kroesbergen, 2011; Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006), nevertheless the predictive value of the amount in which children manage this specific language has, to our knowledge, never been studied in one design together with other precursors.

Present study

There appear to be wide individual differences in the early numeracy level of children starting their early school career and as these differences remain, or even increase, during kindergarten, it could be hypothesized that the developmental path of children with weaknesses in early numeracy differs from that of typically achieving kindergartners. The first aim of the present study is to examine the growth in early numeracy separately for typical achieving kindergartners and weak performing kindergartners. Furthermore, from the research conducted so far, there is ample evidence that working memory, comparison skills, and specific math language can all be seen as relevant precursors of early numerical skills. However, as yet, these possible precursors have not been studied in one design to explain early numeracy growth for kindergartners being at risk for developing math difficulties. Therefore, to fulfill the second aim of the present study, all these above mentioned precursors (working memory, comparison skills, and specific math language) will be taken into account to explain differences in early numeracy in weak performing kindergartners at risk for developing math learning difficulties. The reason for including all of these measures is to compare their predictive value with respect to both the initial level and the growth rate of early numeracy skills. This study examined the following research questions:

1. Is there a difference between the early numeracy development of weak performing kindergartners and typically achieving kindergartners?
2. Which predictors have an effect on the early numeracy development of weak performing kindergartners, and how do the predictive values of these factors relate to each other?

Method

Participants

In this study, 990 children (531 boys, 51.8%) with a mean starting age of 4.55 years (*SD* = 4.02 months) participated. The children attended 26 primary schools in rural or urban areas in the Netherlands.[1] Participating schools were selected to reflect the national demographic profile of children in terms of, first, the number of children in the school and, second, the socio-economic background of the children, according to the classification system developed by the Dutch government that funds primary schools. Parental consent was obtained for all children participating.

A classification into two groups was made, based on early numeracy performance at the first time point (halfway through the first year of kindergarten). This distinction was made as closely as possible to a 15% to 85% proportion of the total group of children: one group with the 18.6% lowest scoring children on the standardized early numeracy test (weak performers, WP), and one group with the 81.4% remaining children (typical performers, TP). The critical cut-off (< 15^{th} percentile) was based on the severeness criterion described by Desoete, Roeyers, and De Clercq (2004). The 184 children (109 boys, 59.2%) in the WP group had a mean age of 4.37 years (*SD* = 3.88 months), while the 806 children (404 boys, 50.1%) in the TP group had a significantly higher ($t(988) = 8.35$, $p < 0.01$) mean age of 4.59 years (*SD* = 3.89). Furthermore, there was a significant association between gender and group classification (χ^2 (1) = 4.99, $p = .03$, $V = .07$), with the WP group containing more males. Therefore, both gender and age were taken into account in the subsequent analyses as covariates to control for the group differences in gender and age. The above analyses were conducted with an alpha of .05.

The children from both groups were followed until the end of the second year of kindergarten, just before they made the transition to formal math education in first grade. During the course of the study, 54 children (5.45%) dropped out because they moved (42 children), or accelerated a year in kindergarten (12 children). Furthermore, 11 children (1.11%) were absent during one of the early numeracy measurements, and seven children (0.71%) during one or more of the other tests. The scores of one child on working memory were assessed as being invalid due to technical errors. Due to the application of full information maximum likelihood (FIML) within Structural Equating

1 In the Netherlands, children begin attending kindergarten when they reach the age of four. They attend, on average, two years of kindergarten before moving to first grade in September of the year in which they turn six years old.

Modeling, all available scores of the missing children remained included in the analyses (Wothke, 2000).

Procedure

Early numeracy abilities were measured with a standardized early numeracy test on four time points throughout kindergarten: halfway (January; H1) and the end (June; E1) of the first year, and halfway (January; H2) and the end (June; E2) of the second year. Working memory and comparison skills were measured at the end (June) of the first year of kindergarten. All working memory tasks were computer tasks, as was the test for specific math language, which was measured halfway (January) through the second year. The children were tested individually in a quiet area of the school for two 20–30 minute sessions. All tasks were obtained in a fixed sequence. All tests were administered by graduate students in education or psychology (university master's degrees), who were trained for testing young children.

Instruments

Early numeracy

The selected children completed the *Early Numeracy Test-Revised* (ENT-R; Van Luit & Van de Rijt, 2009) at four time points to measure early numeracy skills. The ENT-R is a 45-item standardized pencil-and-paper test for children between the ages of four and seven years old. The test consists of nine parts that are indicators of early numeracy. The components can be divided into eight verbal tasks (concepts of comparison, classification, correspondence, seriation, use of numerals, synchronized and shortened counting, resultative counting, and general understanding of numbers) and one non-verbal task (estimation). Each component contains five consecutive items. The total number of correct answers (0 to 45) was used in the analyses. The test contains of two versions: A and B. The reliability coefficient of the test is good for both versions ($\alpha = .93$; Van Luit & Van de Rijt, 2009). Version A was administered at the halfway point of the first and second year of kindergarten, and version B at the end of the first and second year of kindergarten. Four principal component analyses (PCA) with varimax rotation, one for each measurement point, on the nine components were conducted, all revealing one factor explaining between 38.79 and 45.20 of the variance. Results are presented in Table 3.1. Prior to the two PCA, the Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) measure were used to test whether factor analysis is appropriate

Table 3.1 Statistics of principal component analyses, Bartlett's tests of sphericity, the Kaiser-Meyer-Olkin (KMO) and reliability analyses for the Early Numeracy Test-Revised on each time point

	Time point H1	Time point E1	Time point H2	Time point E2
R^2	45.20	40.52	42.08	38.79
Bartlett's χ^2	2664.05	2106.63	2217.47	1818.43
df	36	36	36	36
p	.00	.00	.00	.00
KMO	.92	.90	.91	.89
α	.84	.81	.82	.80

Note. H1 = halfway through first year of kindergarten, E1 = end of first year of kindergarten, H2 = halfway through second year of kindergarten, E2 = end of second year of kindergarten.

for these data. The Bartlett's Test of Sphericity was significant for all four time points (Table 3.1), which means that there are some relationships between the variables, and all four KMO measures fell into the large range (Hutcheson & Sofroniou, 1999). On the basis of both statistics, it can be concluded that factor analyses are appropriate for the four time points. Reliability analyses revealed good internal consistency of the factor for the four time points (Table 3.1).

Working memory

Working memory ability was measured with two computer-based tasks from the *Automated Working Memory Assessment* (AWMA; Alloway, 2007), which was translated into Dutch and voice-recorded. The AWMA has a stable construct validity and good diagnostic validity for children with low working memory skills. For children aged 4.5 and 11.5 years old, the test-retest reliability of the two tasks was 0.81 and 0.74, respectively (Alloway et al., 2008). Both working memory tasks started with a short practice session and were automatically terminated when a child gave three incorrect answers within a set of items of the same length.

Visual working memory. Visual working memory was measured by the *Odd One Out* task, in which children were asked to point out the odd shape in a row of three geometrical shapes, and to remember the location of this shape. Then three new shapes appeared. At the end of each trial, three empty boxes appeared and the children were asked to point to the consecutive locations of the odd shapes. The test started with a set of one trial, building up to a block with a sequence of seven trials within a set. The number of correctly recalled trials was recorded for sets in which all items were recalled correctly. The scores could range from zero to 28.

Verbal working memory. Verbal working memory was measured by the *Word Recall Backwards* task. In this task, a recorded voice names a series of semantically unrelated one-syllable words, after which the child is asked to repeat the words in reverse order. The string of words becomes more and more extensive (starting with two words and building up to a string of seven words) after a child has recalled four strings correctly and in the correct order. The number of correctly recalled series was recorded for sets in which all trials were recalled correctly. The scores could range from zero to 24.

The scores for the two working memory tasks represent the number of correct answers given for these tasks. These scores can be considered as valid only if there are no extreme values identified (Tabachnick & Fidell, 2006). For that reason, univariate outliers, scores differing by three standard deviations or more from the mean, were removed. This procedure was carried out for two scores on Odd One Out, and no scores on Word Recall Backwards.

Comparison skills

Two comparison tasks were administered to test the children's ability to discriminate between quantities (non-symbolic comparison) or between the values of number symbols (symbolic comparison). In both tasks, the child received two practice items, but no prompts were given during the actual tasks.

Non-symbolic comparison. In the non-symbolic comparison task, the child was asked to compare two arrays with dots and had to indicate the array with the highest number of dots. The dots varied not only in number but also in size (Barth et al., 2006; Gebuis, Cohen Kadosh, de Haan, & Henik, 2009). To control for non-numerical parameters (such as dot size, covered surface, density) three conditions could be distinguished: (1) congruent condition in which the area with the largest number of dots was also physically larger, (2) incongruent condition in which the area with the largest number of dots was physically smaller, and (3) a neutral condition in which the physical size of the dots in both areas was the same but the number varied. In each condition, 10 trials were presented with the amount of dots ranging from one to 100. The dependent measure was the number of items (30 in total) solved correctly. Although few studies reported the reliability of the non-symbolic comparison task, the task is frequently used as a measure of quantity discrimination (e.g., Iuculano et al., 2008; Malofeeva, Day, Saco, Young, & Ciancio, 2004). The internal consistency of this comparison measure was good in this study (α = .87), and also in another study (α = .93) (Boonen et al., 2011).

Symbolic comparison. In the symbolic comparison task, children were asked to indicate the number with the highest numerical value out of two numbers presented in two frames. The three conditions and number of trials (30) were the same as in the non-symbolic task, except for the stimuli: instead of using dots, number symbols were used. The internal consistency based on the data in the current study, as well as the test-retest reliability of this task in another study (Clarke & Shinn, 2004), was acceptable (α = .67).

Specific math language

To measure the mastery of specific math language, the subtest "sentence structures" from the *Language Test for All Children* (Verhoeven & Vermeer, 1993) was administered. In this task, a sentence was presented to the children that corresponded with one of three pictures. Only the 24 items focusing on "quantity words" (e.g., half, equal, more) or "spatial words" (e.g., behind, between, opposite) were used as an indicator of specific math language. The total number of correct answers (zero to 24) was used in the analyses. The reliability coefficient of the subtest was good for this age range (α = .85; Verhoeven & Vermeer, 2006).

Statistical analyses

The statistical analyses were carried out in four steps. First, the descriptive statistics of the two groups were explored. Second, the relations between the four early numeracy scores and the predictor variables were explored with correlation analyses for both groups separately. Third, two analyses – steps 3 and 4 – were performed using Latent Variable Growth Curve Modeling within a structural equation modeling framework using the Mplus statistical package (Version 6; Muthén & Muthén, 1998–2010). In the third step, Multi Group Latent Variable Growth Curve Modeling was used to investigate the growth rate of early numeracy and the association between the initial level of early numeracy and its developmental trend across time, separately for both groups (Byrne, 2012). In order to test for differences between the two groups, their parameters (intercept and slope value) were compared using two Wald chi-square tests. In the fourth and final step, individual differences within the weak performers' group (WP) in the initial level (intercept) and the rate of growth (slope) of early numeracy were predicted by different cognitive antecedents and age.

The data have a nested structure, with children nested in schools. Ignoring the multilevel structure might have led to unreliable standard errors of the coefficients of the model (Hox, 2010). According to Hox, Schoot, and Matthijsse (2012) the number of schools in this study (26 schools) did not allow a multilevel model including predictors on the highest level. Therefore in both models – steps 3 and 4 – the standard errors were corrected for the nested structure using an automatic multilevel modeling setup (Stapleton, 2006). The Mplus statement “type is complex” makes that part of the model-variance is attributed to between-school variance (i.e., variance in achievement outcome existing between schools) rather than only to within-school variance.

As is common in structural equating modeling, overall model fit is indicated by several fit indices, which each evaluate different aspects of the model. In this study, goodness-of-fit was evaluated with three indicators recommended by Blunch (2008): chi square (χ^2) with its p-value, comparative fit index (*CFI*), and root mean square error of approximation (*RMSEA*) with its p_{close}-value. Chi-square should be as low as possible, with a p-value that is as high as possible. *CFI* is good if *CFI* > 95 and acceptable if *CFI* > 0.90. *RMSEA* is good if < 0.05 and acceptable if < 0.08. Its p_{close}-value should be high.

Results

Descriptive statistics

Table 3.2 provides mean raw scores and standard deviations for early numeracy at the four measurements, verbal and visual working memory, non-symbolic and symbolic comparison skills and math language, parsed by group, WP and TP, and for the total group. Preliminary analyses show significantly higher scores for the TP children than the WP children on all nine measurements with a minimum t-value of 5.75 (df = 926, p < .01) for non-symbolic comparison, and a maximum t-value of 41.65 (df = 934.82, p < .01) for early numeracy halfway through the first year of kindergarten, which was the criterion score for group classification.

Correlation analyses

In the next step, the correlations between the nine measurements were investigated for the WP and TP groups separately (Table 3.3). All correlations were low to moderate. There was no indication of multicollinearity problems in the subsequent analyses. Note that when comparing both groups, some similar correlations reach significance for the TP group, but not for the WP group, which can be ascribed to a smaller number of children in this group. For both groups, significant correlations were found between

Table 3.2 Descriptive statistics of all nine measurements for the two groups and the total group

	Weak performers			Typical performers			Total group		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
Early numeracy H1	184	6.15	1.84	806	16.89	6.22	990	14.89	7.04
Early numeracy E1	177	11.62	3.93	797	19.00	5.96	974	17.66	6.32
Early numeracy H2	172	21.26	7.01	770	29.10	6.32	942	27.67	7.16
Early numeracy E2	166	23.77	6.69	769	29.68	5.48	935	28.63	6.14
Visual WM	169	5.80	1.99	756	7.74	2.67	925	7.39	2.67
Verbal WM	170	1.58	1.92	757	3.77	2.00	927	3.37	2.16
NS comparison	171	21.15	5.24	757	23.86	5.63	928	23.36	5.65
S comparison	171	16.13	4.06	757	20.28	6.07	928	19.52	5.97
Math language	171	17.02	3.00	770	19.51	2.10	941	19.06	2.48

Note. WM = working memory, NS = non-symbolic, S = symbolic, H1 = halfway through first year of kindergarten, E1 = end of first year of kindergarten, H2 = halfway through second year of kindergarten, E2 = end of second year of kindergarten.

Table 3.3 Results of correlation analyses for all nine measurements for the two groups

Weak performers	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Early numeracy H1	–								
2. Early numeracy E1	.43**	–							
3. Early numeracy H2	.23**	.44**	–						
4. Early numeracy E2	.32**	.49**	.60**	–					
5. Visual WM	.24**	.23**	.13	.11	–				
6. Verbal WM	.17*	.39**	.41**	.38**	.15	–			
7. NS comparison	.24**	.32**	.33**	.22**	.23**	.15	–		
8. S comparison	.16*	.30**	.28**	.26**	.24**	.32**	.49**	–	
9. Math language	.28**	.45**	.43**	.48**	.17*	.33**	.21**	.17*	–

Typical performers	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Early numeracy H1	–								
2. Early numeracy E1	.70**	–							
3. Early numeracy H2	.48**	.59**	–						
4. Early numeracy E2	.46**	.60**	.59**	–					
5. Visual WM	.36**	.40**	.29**	.25**	–				
6. Verbal WM	.37**	.42**	.39**	.34**	.28**	–			
7. NS comparison	.21**	.23**	.16**	.21**	.10**	.11**	–		
8. S comparison	.44**	.48**	.37**	.38**	.23**	.26**	.62**	–	
9. Math language	.24**	.34**	.34**	.30**	.22**	.22**	.12**	.22**	–

Note. ** $p < .01$ * $p < .05$, WM = working memory, NS = non-symbolic, S = symbolic, H1 = halfway through first year of kindergarten, E1 = end of first year of kindergarten, H2 = halfway through second year of kindergarten, E2 = end of second year of kindergarten.

all four measurements on early numeracy. Notable differences between the two groups mainly have to do with visual working memory. In the WP group, this score is not related to early numeracy halfway through and at the end of the second year, nor to verbal working memory, while this is not the case for TP group. Furthermore, in contrast to the TP group, no relation between verbal working memory and non-symbolic comparison and between symbolic comparison and early numeracy halfway through the first year was found for the WP group.

Multi group latent variable growth curve modeling

To investigate the growth dynamics of early numeracy performance, a multilevel latent growth curve model for the four early numeracy measurements was created. In this model (Figure 3.1) with two growth factor components, the intercept (initial

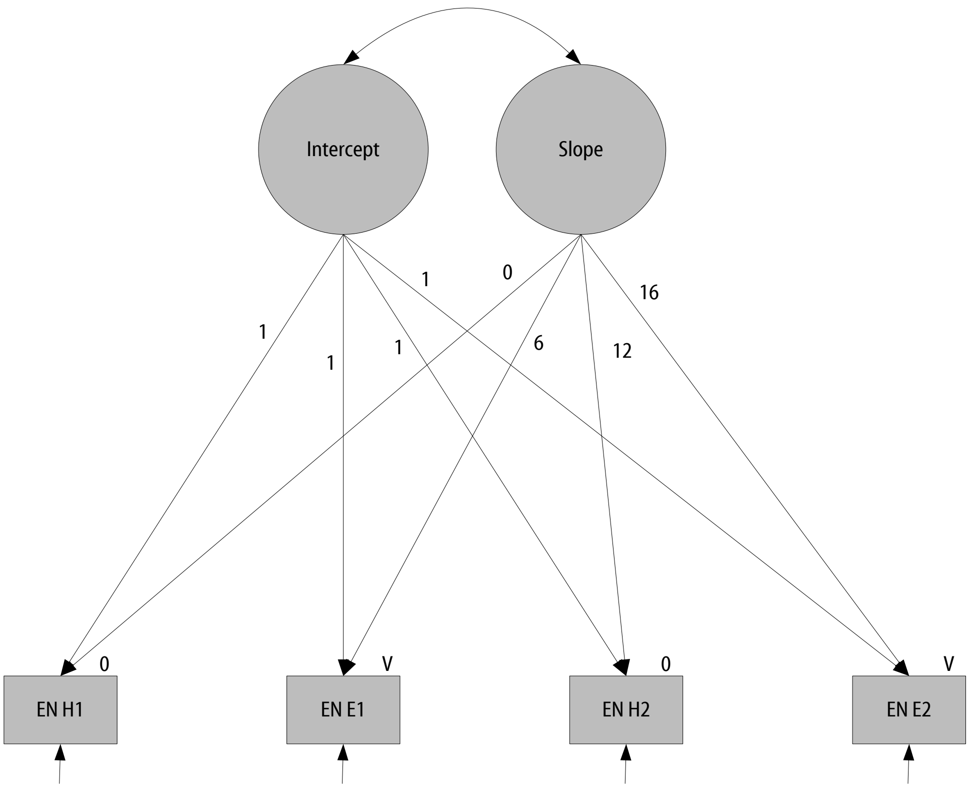

Figure 3.1 Latent growth curve model for early numeracy performance with fixed loadings. EN = Early Numeracy, H = halfway through school year, E = end of school year, 0 = zero bij default, V = version; freely estimated, but constrained to be equal.

level) and the slope (linear growth rate), the loadings of the observed early numeracy performances across time were fixed to 1 on the intercept and to 0, 6, 12, and 16 on the slope, in accordance with the number of months between the different measurements (Biesanz, Deeb-Sossa, Papdakis, Bollen, & Curran, 2004). The means of the observed early numeracy performances halfway the first year (H1) and halfway the second year (H2) were zero by default (see Figure 3.1: 0). However, the other two means (E1 and E2) were constrained to be equal, but were allowed to be freely estimated (see Figure 3.1: V). By doing so, for all children a constant difference with the originally value was realized at these two time points. This was done to correct for the difference in versions of the early numeracy test between H1 and H2 (version A) and E1 and E2 (version B). To test this model separately for the WP and TP group a grouping comment was added. This means that all the parameters were estimated separately for each group.

The fit indices of the overall model were $\chi^2(9) = 36.73$, $p < .01$, $CFI = .97$, $RMSEA = .08$, $p_{close} = .04$. The χ^2 contributions from each group were 23.05 for the WP group and 13.68 for the TP group. The low *p*-value of the chi-square can be considered acceptable due to the large amount of children included in the model (Byrne, 2012; MacCallum, 1990). The standardized estimated of the means, residual variances, loadings, and parameter values are presented in Table 3.4. The results reveal that the variance around the intercept (WP: 2.73, $p < .01$; TP: 16.72, $p < .01$) and the variance of the slope (WP: 0.11, $p < .01$; TP: 1.04, $p < .01$) were statistically significant, indicating that within the groups there were significant individual differences in these two growth components. Although a significant relation was found between the intercept and the slope for the TP group, this was not the case for the WP group. This implies that among the TP group, children performing low at the start have a faster development.

The first Wald's test, regarding the unstandardized mean of the intercept, shows a significantly higher initial level for the TP group compared to the WP group (WP: 6.19; TP: 16.72; $Wald(1) = 756.91$, $p < .01$). The high Wald-value can be partially explained by the classification based on the first measurement of early numeracy. More interestingly, regarding the unstandardized mean of the slope, a significantly higher growth rate for the WP group was found compared to the WP group (WP: 1.33; TP: 1.04; $Wald(1) = 56.71$, $p < .01$), indicating faster development for the weak performing children in early numeracy throughout kindergarten than the typically performing children.

Table 3.4 (Un)standardized results of multi group latent variable growth curve modeling on early numeracy

	Unstandardized mean	Unstandardized residual variance	Standardized loading intercept	Standardized loading slope	Standardized intercept mean	Standardized slope mean	Standardized correlation I–S
Weak performers					3.75	4.04	.11 (ns)
Early numeracy H1	0.00	0.64 (ns)	.90				
Early numeracy E1	-3.63	10.49	.39	.47			
Early numeracy H2	0.00	27.89	.24	.57			
Early numeracy E2	-3.63	11.57	.25	.79			
Typical performers					3.04	3.73	-.55
Early numeracy H1	0.00	9.27	.88				
Early numeracy E1	-3.63	10.52	.95	.29			
Early numeracy H2	0.00	19.04	.87	.52			
Early numeracy E2	-3.63	7.93	.99	.79			

Note. Mean and residual variances (first two columns) are unstandardized; values in other columns are standardized. ns = non-significant, H1 = halfway through first year of kindergarten, E1 = end of first year of kindergarten, H2 = halfway through second year of kindergarten, E2 = end of second year of kindergarten.

3

Predicting initial level and growth in early mumeracy performance of weak performing kindergartners

For the WP group, both the variance around the intercept and the slope were significant, indicating individual differences in these two growth components. Thus, the next step was to investigate the extent to which various cognitive variables, that is, visual and verbal working memory, non-symbolic and symbolic comparison skills, and math language, can predict the intercept and slope components of early numeracy performance. In order to do so, the previous multilevel model was extended for only the children in the WP group. In this model, the predicting variables, together with age and gender, were added as covariates. In the previous model, no significant relation was found between the intercept and the slope for the WP group. As a result, this correlation was fixed to zero. The fit indices of this model were good, $\chi^2(25) = 26.48$, $p = .38$, $CFI = .99$, $RMSEA = .02$, $p = .85$. After omitting non-significant paths and excluding

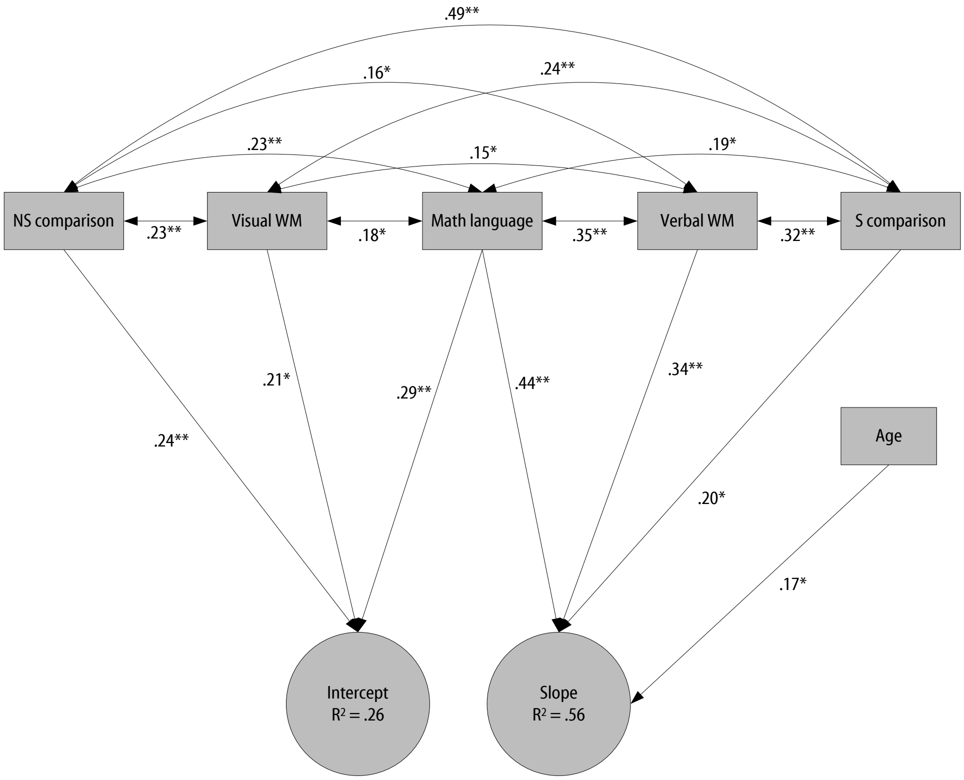

Figure 3.2 Predictors of latent intercept and slope of early numeracy of weak performers (standardized estimates). ** $p < .01$ * $p < .05$, WM = working memory, NS = non-symbolic, S = symbolic.

gender from the model, the fit indices of the model remained good, $\chi^2(27) = 29.45$, $p = .34$, $CFI = .99$, $RMSEA = .02$, $p = .84$. This final model is shown in Figure 3.2. In order to increase clarity, the part of the model representing the four observed early numeracy performances and the latent loadings is not displayed. The standardized estimates for this part can be found in Table 3.4.

The model shows three interesting results. First, the intercept was predicted by three of the predicting covariates. The higher the level of non-symbolic comparison, visual working memory, and math language, the higher was the initial level of early numeracy. These three predictors explained 24% of the variance. Second, the slope was positively predicted by math language, verbal working memory, symbolic comparison, and age. The higher the level of these abilities and the older the child, the faster was their development in early numeracy throughout kindergarten. A large amount of variance (56%) could be explained by these four variables. Third, all five covariates are significantly related to each other, with correlation ranging from .15 (visual and verbal working memory) to .49 (non-symbolic and symbolic comparison).

Discussion and conclusion

The main objective of this study was to examine precursors of early numeracy development in kindergartners with insufficient numeracy skills. The study was designed to compare the predictive value of working memory, comparison skills, and specific math language on the development of early numeracy in weak performing four and five year olds. To meet this objective, two research questions were formulated. Regarding the first question, it can be concluded that differences in the growth rate exist between typically achieving children (scoring above the 15th percentile) and children with insufficient mathematical difficulties (scoring below the 15th percentile). Although differences were rather small in the present study, the growth of early numeracy was faster among those who entered preschool with a low level of early numeracy. This is in line with other studies on early numeracy growth (e.g., Jordan et al., 2006), but also incongruent with the results of other studies on early numeracy (Aunio, Hautamäki, Sajaniemi, & Van Luit, 2009) and formal math achievement (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). The results suggest that children who enter kindergarten with a relatively low early numeracy level have more opportunities to improve their skills in early numeracy when they enter kindergarten, and thus, implies that those children profit from the offered (remedial) curriculum in their kindergarten. An implication that is identified by this conclusion is the emphasis on the importance of intervention on early numeracy. It is desirable to investigate the possibility of preventive interventions for preschoolers and school beginners who have not yet begun to fail in school (Dowker, 2005) because it is expected that effective early math interventions would decrease the number of children who are retained in first grade (Moser, West, & Hughes, 2012). Recently conducted studies show an effect of a targeted small-group early numeracy intervention for high-risk kindergartners from low-income communities, on both number competencies and general math achievement (e.g., Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012).

Regarding the second research question, focusing on the predictive value of different factors, three main conclusions can be drawn. First, it can be concluded that, in line with previous research (Espy et al., 2004; Kroesbergen et al., 2007; Kyttälä et al., 2009), working memory indeed plays an important role in early numeracy skills. More specifically, visual working memory seems to predict variance on the initial status, while verbal working memory has meaningful influence on the development of early numeracy. This confirms the results of studies discussed by Raghubar and colleagues (2010), suggesting visual–spatial working memory to be more specific to early mathematical learning, and other executive processes to be more generic in terms of supporting learning. The second conclusion concerns the discussion of whether non-symbolic or symbolic skills are more important for early numeracy. In this study, non-symbolic comparison skills proved to be important for the intercept and symbolic, whereas comparison skills explained the slope value, suggesting that symbolic skills are more important and therefore support the view that non-symbolic skills seemed to play a subordinate role in learning math in contrast to the important role of symbolic skills (Holloway & Ansari, 2009; LeFevre et al., 2010; Rousselle & Noël, 2007). The next step in research among this group of children should include numerical mapping skills, in which number words and symbols are mapped onto their corresponding magnitude (Mundy & Gilmore, 2009). Finally, and most remarkably, specific math language (numerical concepts such as more and less and spatial concepts such as behind and above) shows the highest contribution of prediction of both the early numeracy intercept and the early numeracy slope of kindergartners lagging behind. The predictive value is most important, even above the predictive value of working memory and comparison skills, which are factors that are investigated far more frequently in relation to early numeracy. Stating the importance of math-related language is congruent with Lansdell (1999). She proposes the introduction of this “new” terminology as an important part of the teaching of early mathematical concepts. Because knowledge on this subject is still scarce, while it turns out to be of great importance, further research is necessary to examine this relation more closely.

The above formulated conclusions imply that the factors considered in the present study, especially verbal working memory, symbolic comparison skills, and math language, might be good predictive measures for identifying at an early stage children at risk of developing learning difficulties. Therefore it could be helpful to include these precursors in screening batteries in kindergarten, and so contribute to the screening process of children at risk of learning difficulties. Whereas working memory tasks are beginning to become available (e.g., AWMA; Alloway, 2007) and comparison skills are often part of early numeracy screening tests, less standardized options tend to be available to measure the mastery of specific language being important to understand mathematical transformations. Nowadays, measuring general language achievement is part of the curriculum in a lot of preschools and kindergarten, but because these skills are insufficient for identifying gaps that can influence early numeracy development and the origin of math learning difficulties, designing a more specific test on math language could be highly valuable. Besides testing these concepts, the importance of math-related language should be better acknowledged within the educational setting, in other words it should be better included and imbedded within the curriculum. Following Lansdell (1999), there are a few recommendations for teachers to avoid serious misunderstandings in children's learning of this math language, including the awareness of "ambiguous" words, the consciousness and consistency of their own use, assessments for children's understanding of new concepts, and the introduction of new meaning in context once the concepts are understood.

A limitation of this study is the use of a standardized early numeracy test with only an overall early numeracy score, unless nine components are distinguished within the test structure. Unfortunately, factor analyses revealed only one factor, thus it is undeserved to split this score into specific skills; however, it would be highly interesting to find relationships for the specific skills. Further studies are needed to understand the developmental differences in subcomponents of math performance. Also, a direct comparison with other interest groups such as second language learners or children with specific language impairment (SLI), as is done in the research of Kleemans, Segers, and Verhoeven (2011a, 2011b), would be beneficial for further research. Another limitation has to do with the selection criterion in the present study. Although the cut-off criterion used in the present study (> the 15th percentile) is deliberately chosen and can be seen as strict, most studies use a cut-off score of two standard deviations below the mean (e.g., Desoete et al., 2004). This difference should be taken into account when directly comparing the results of different studies.

In this study, some specific precursors were chosen, from which the influence of early numeracy was examined in children with weak early numeracy. The set of precursors was limited, and did not include, for example, processing time (e.g., Berg, 2008), attention (e.g., Swanson, 2011), shifting (e.g., McLean & Hitch, 1999), and inhibition (e.g., Bull & Scerif, 2001). Moreover, environmental, educational, family, or motivational variables may also play a role (Anders et al., 2012; Melhuish et al., 2008). Nevertheless, the results of this study show an effect of verbal working memory, symbolic comparison skills, and math language on the development of at-risk-children's numeracy. Therefore, these factors must be taken into account in further research on this specific area of education.

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The developmental relationship between language and low early numeracy skills throughout kindergarten

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Exceptional Children (in press).

Abstract

The relationship between basic oral language and early numeracy has been studied extensively, but results hardly include kindergartners' math language, that might mediate this relationship. The aim was to investigate the development of basic language skills, specific math language and low early numeracy. 1030 Dutch (4-5 years old) children were screened for having low early numeracy skills. 199 low-performers were followed for two years and tested four times throughout kindergarten. The development of general language skills and early numeracy were investigated using latent growth modeling, revealing a significant mutual relationship. Furthermore, the relationship between basic language and early numeracy was mediated by kindergartner's specific math language, suggesting specific math language as a key role in the early numeracy learning process.

Introduction

Low early numeracy

A growing body of research focuses on the consequences of low early numeracy in preschoolers and kindergartners (Aunio, Hautamäki, Sajaniemi, & Van Luit, 2009; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Locuniak & Jordan, 2008; Stock, Desoete, & Roeyers, 2010; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011). Early numeracy can be defined as the general understanding of numbers (Gersten et al., 2012; Passolunghi & Lanfranchi, 2012) and can be divided into several skills including (verbal) counting, knowing the number symbols, recognizing quantities, discerning number patterns, comparing numerical magnitudes and estimating quantities (Desoete, Ceulemans, De Weerdt, & Pieters, 2010; Fuchs, Fuchs, & Compton, 2012; Gersten, Jordan, & Flojo, 2005; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011).

It is generally accepted that children with inadequate early numeracy skills are at risk for developing mathematical learning difficulties at a later stage. These children already trail behind in their early numeracy knowledge by the age of five and are at high risk for developing mathematical learning difficulties in primary school (Toll et al., 2011), and even further along in the curriculum (Duncan et al., 2007; Siegler, 2009). Therefore, it is important to effectively predict which kindergartners are at risk for math learning difficulties based on early numeracy scores obtained during kindergarten (Mazzocco, 2005; Mazzocco & Thompson, 2005).

General oral language and (low) early numeracy

Early numeracy development mainly takes place in the years before formal education in the first grade. Another important skill that develops rapidly during the kindergarten years is language acquisition. It has been well documented that children entering kindergarten differ in their language and early numeracy skills (Fuchs, Geary, et al., 2010) and that these differences are often maintained at later ages (e.g., Tymms, Merrell, & Henderson, 1997). Both skills, early numeracy and basic language, appear to be related to each other in typical developing children, and these skills, like other cognitive skills, are likely to influence each other mutually during development (Schmittel & Bass, 2012). However, less is known about this interrelationship in children with inadequate early numeracy skills. A longitudinal design can capture more of these complex relationships as it can capture the relationship between growth in language and growth in early numeracy, even though the exact direction of these hypothesized, mutually causal relationships is difficult to determine.

In general, it is assumed that language is one of the main inputs for learning and for this reason, the acquisition of early numeracy skills is highly dependent on basic oral language (e.g., Duncan et al., 2007; Spelke & Tsivkin, 2001). Therefore, it has been argued that adequate language skills are a prerequisite for learning early mathematics (Aiken, 1972; Dehaene, Piazza, Pinel, & Cohen, 2003). Language skills are related to concurrent mathematical performance as well as predictive of later mathematical performance (Hooper, Roberts, Sideris, Burchinal, & Zeisel, 2010; Romano, Babchishin, Pagani, & Kohen, 2010).

Considering that the studies mentioned above unveil and acknowledge the linguistic challenges of teaching and learning mathematics, it is surprising that relatively little is known about the relationships between kindergartners' oral language skills and early numeracy proficiency, in particular and especially in children with low early numeracy. Therefore in the present study, this developmental relationship throughout kindergarten is examined in a group of children with (very) low early numeracy skills. More insight into the relationship between basic language and early numeracy can lead to greater understanding of how early numeracy skills of at-risk kindergartners develop and help to identify potential barriers to successful acquisition of these skills. Furthermore, understanding how children's higher order language skills interfere with, or support, the development of numeracy proficiency also appears to be critical to closing the mathematical achievement gap at a later stage in the educational career of those children.

The present study investigates the role of general oral language. Basic oral language skills include word knowledge, vocabulary, and understanding grammatical rules (Storch & Whitehurst, 2002). These skills have proven to be individually related to, and predictive of, young children's general numeracy knowledge, and moreover, are uniquely predictive of later numeracy performance when accounting for initial numeracy performance and nonverbal cognitive ability (Purpura et al., 2011). Basic oral language skills may furthermore predict mastery of more complex numeracy tasks later in childhood (Duncan et al., 2007).

Besides oral language, other components of language (i.e., phonological processing and print knowledge) are discussed and investigated drawing on previous research exploring the relationship between language and early mathematics in a sample of typical developing children. These components are related to (one or more domains of) early numeracy. Phonological awareness, for instance, has been related to quantity number competences (Krajewski & Schneider, 2009) and informal mathematics (Alloway et al., 2005) in early childhood. Additionally, problems in phonological awareness affect aspects of arithmetic that involve the manipulation of verbal codes (Simmons & Singleton, 2008). However, Purpura, Hume, Sims, and Lonigan (2011) did not find phonological awareness as a unique predictor of numeracy development. Moreover, they found that print knowledge, a child's knowledge of letter names and sounds, words, and basic conventions about books and print (Whitehurst & Lonigan, 1998), was a strong predictor of early numeracy.

Specific math language and (low) early numeracy

One part of basic oral language that has been hypothesized to be especially important for the development of mathematical ability is the language that includes math-related concepts such as "more," "less," "higher" and "lower" that can be used to compare or classify objects or amounts, but also concepts such as "whole" or "half," or more spatial concepts such as "below" or "above" (Pruden, Levine, & Huttenlocher, 2011). Mathematics vocabulary needed for effective learning is extensive, and includes words referencing counting and recognizing numbers (e.g., individual number names, "how many," "count," "tens," "more," "odd"), adding and subtracting (e.g., "add," "more," "fewer," "altogether," "difference"), solving problems (e.g., "pattern," "compare," "list," "answer," "left over," "price"), and words involving concepts such as measures, patterns, time, shape and space (e.g., "size," "compare," "length," "depth," "opposite," "triangle," "sphere") (see Department of Education and Employment, 2000, for a more comprehensive list).

It has been repeatedly suggested that language and early numeracy skills may be linked because an understanding of certain specific language terms is inherently necessary for the completion of basic mathematical tasks (e.g., Sarnecka & Gelman, 2004). Lansdell (1999) proposes the introduction of this 'new' terminology as an important part of teaching early mathematical concepts. Learning the 'language' of the academic subject is part of developing early numeracy proficiency, just like developing proficiency in any other area. However, empirical evidence on this matter in low early numeracy performance is lacking. It has been shown that some children experience particular difficulties in this specific math language but develop normally in general language (Ginsburg, 1972; Schleppegrell, 2010). Still, specific math language as an integral part of the development of numeracy knowledge has never been specifically investigated.

The fact that some children have particular math language difficulties indicates that specific math language might facilitate the use of numerical concepts and that having weak number knowledge affects learning of specific math language (Gelman & Butterworth, 2005; Halberda, Taing, & Lidz, 2008). Educational research shows the positive impact of kindergarten teachers' use of this specific math language (Boonen, Kolkman, & Kroesbergen, 2011; Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006). Consequently, this specific math language is often found in mathematical assessments, interventions, and curricula. Hence, the aforementioned studies propose this specific math language to be a mediating factor in the relation between language and (low) early numeracy. Nevertheless, the mediating role of this specific math-related language has never been examined in a longitudinal design throughout kindergarten.

Present study

From the research conducted so far, there is ample evidence that language and early numeracy are interrelated in typical developing children around the age of five. Nevertheless, not much is known about this relationship in kindergartners with low early numeracy and about the role specific math language plays in this relationship. To clarify the relations between general language, specific math language and numeracy within this target group of at-risk kindergartners, the present longitudinal study had three aims. The first aim of the study was to separately investigate the development of general basic language skills and early numeracy longitudinally. Latent variable growth curve models were built to model the development of each skill separately. The next aim was to examine whether these skills develop mutually. That is, whether the relationship between these two important skills influence each other reciprocally. Finally, this study aims to test whether this mutual relationship remains when including children's knowledge about specific math language as a mediating factor between general language and early numeracy. Specifically, the following research questions were addressed:

1. Is there a mutual relationship between language development and early numeracy development in kindergartners with (very) low early numeracy?
2. Does specific math language mediate the relationship between general language development and early numeracy in kindergartners with (very) low early numeracy?

Method

Participants

A total of 1030 children (533 boys, 51.7%) with a mean age of 4.56 years (SD_{age} = 4.07 months) were screened for (very) low early numeracy with the standardized Early Numeracy Test – Revised (ENT-R; Van Luit & Van de Rijt, 2009). The children attended the first year of kindergarten in 30 primary schools in rural or urban areas in the Netherlands. In the Netherlands, children begin attending kindergarten when they reach the age of four. They attend, on average, two years of kindergarten before moving onto the first grade in September of the year they turn six years old. Kindergarten, in the Netherlands, is similar to Pre-K and K in the United States of America. Participating schools were selected to reflect the national demographic profile of children in terms of, first, the number of children in the school and, second, the socio-economic background of the children according to the classification system developed by the Dutch government that funds primary schools. Parental consent, in line with Institutional Review Board procedures, for all children participating was obtained.

Within all schools, children received early numeracy education for approximately 1 hour per week following a curriculum chosen by the school. These instructional methods were referred to as *Wizwijs*, *Schatkist*, *Pluspunt*, *Alles telt*, or *The road to mathematics*. The methods aim to provide class wise instruction covering multiple early numeracy domains such as comparison, classification, counting, recognizing numbers, time and space and measurement and geometry. Throughout, all schools attempted to comply with the Dutch kindergarten objectives regarding early numeracy (e.g., Gelderblom, 2007).

The mean early numeracy score of the screened children was 14.77 (SD_{score} = 7.09). A selection of children with (very) low early numeracy was made as closely as possible to selecting children scoring below the 15th percentile, resulting in a selection of the 19.6% lowest scoring children on the standardized early numeracy test. The critical cut-off (< 15th percentile) was based on the severity criterion described in several previous studies (Desoete, Roeyers, & De Clercq, 2004; Seethaler & Fuchs, 2010) and, furthermore, reflected the criteria of scoring below one standard deviation (7.09) from the mean (14.77), an often applied criterion for selecting at-risk pupils (Murphy, Mazzocco, Hanich, & Early, 2007). Our selected sample included 199 children (118 boys, 59.3%) who showed poor early numeracy. These children had a mean age of 4.41 years (SD_{age} = 4.23 months) which was significantly lower than the mean age (M_{age} = 4.59 years, SD_{age} = 3.92 months) of the unselected children, $t(1026) = 6.923$, $p < .01$. The selected sample also included slightly more boys, $\chi^2(1) = 5.63$, $p = .02$. All analyses above were conducted with an alpha of .05.

The selected children, identified as having (very) low early numeracy, were followed until the end of the second year of kindergarten, just before they made the transition to formal math education in the first grade. During the course of the study, 15 children (7.5%) dropped out because of moving to another city. Furthermore, 8 children (4.0%) were absent during one of the measurements due to illness. With the application of full information maximum likelihood (FIML) within Structural Equating Modeling, all available scores of the missing children were included in the analyses (Wothke, 2000).

Procedure

Institutional review board approval, provided by the ethical committee of the faculty of social and behavioral sciences at Utrecht University, was received for this study. General language skills and early numeracy abilities were measured at four time points throughout kindergarten: halfway through (January; H1) and at the end (June; E1) of the first year, and halfway through (January; H2) and at the end (June; E2) of the second year. Specific math language was measured halfway through the study in January of the second year. Assessing specific math language at this time point allowed the best overall level of specific math language because all children received a similar amount of education in kindergarten and therefore the score represents how much they have learned in school so far. The early numeracy test and the computer-based specific math language test were administered by graduate students in education or psychology (university master's degree) who were trained for testing young children. The children were tested individually in a quiet area of the school. The general language tests were standardized and administered in groups by the teacher.

Instruments

Early numeracy. The selected children completed the ENT-R (Van Luit & Van de Rijt, 2009) at four time points to measure early numeracy skills. The ENT-R is a 45-item standardized pencil-and-paper test for children between the ages of four and seven years old. The test consists of nine parts that are indicators of early numeracy (concepts of comparison, classification, correspondence, seriation, use of numerals, synchronized and shortened counting, resultative counting, general understanding of numbers, and estimation). Each component contains five consecutive items. The total number of correct answers (0 to 45) was used in the analyses. The test contains two versions: A and B. Version A was administered halfway between the first and second year of kindergarten and version B at the end of the first and second year of kindergarten. The reliability coefficient of the test was good for both versions ($\alpha = .93$; Van Luit & Van de Rijt, 2009). Also in the current sample, internal reliability was good for all four time points (H1: $\alpha = .86$; E1: $\alpha = .84$; H2: $\alpha = .85$; E2: $\alpha = .82$). Alternate form reliability was $r = .76$ in the first year and $r = .67$ in the second year.

General language. General language skills were measured by two versions (first year and second year) of the criterion-based *Cito language for kindergartners* (CLK; Lansink, 2009). This is a standardized national Dutch test with good psychometric properties that is commonly used in Dutch schools to monitor the progress of language skills of kindergartners. The first year version contains 48 items and the second year version contains 60 items. Two domains are covered and divided into categories. The first domain, conceptual awareness, consists of passive vocabulary and critical listening, while the second domain, language consciousness, consists of sound and rhyme, hearing the first and the last word, auditive synthesis, and writing orientation. Raw scores are converted into competence scores that increase throughout the school period, enabling the comparison of results from the two versions. The reliability coefficients (α) at each time point are good: .87, .84, .89 and .87, respectively (Lansink & Hemker, 2012).

Specific math language. To measure the mastery of specific math language the subtest ‘sentence structures’ from the *Language Test for All Children* (Verhoeven & Vermeer, 1993) was administered. In this task, a sentence was presented to the children that corresponded with one of three pictures. Only the 22 items focusing on ‘quantity words’ (e.g., half, equal, more) or ‘spatial words’ (e.g., behind, between, opposite) were used as an indicator of specific math language. The total number of correct answers (0 to 22) was used in the analyses. The reliability coefficient of the subtest was good for this age range (α =.85; Verhoeven & Vermeer, 2006).

Statistical analyses

The statistical analyses were performed using Latent Variable Growth Curve Models, a technique that uses Structural Equation Modeling using the Mplus statistical package (Version 6; Muthén & Muthén, 1998-2010). As is common in Structural Equating Modeling, the overall model fit is indicated by several fit indices which each evaluate different aspects of the model. In this study, goodness-of-fit was evaluated with three indicators recommended by Blunch (2008): chi square (χ^2) with its p-value, comparative fit index (*CFI*), and root mean square error of approximation (*RMSEA*) with its p_{close}-value. The value of the chi-square should be as low as possible with a p-value that is as high as possible. A p-value below .05 for the chi-square can be considered acceptable in the present study due to the number of children included in the model (Byrne, 2012; MacCallum, 1990). *CFI* is considered good with a value greater than 0.95 and acceptable with a value greater than 0.90. *RMSEA* is good with a value less than 0.05 and acceptable with a value less than 0.08. Its p_{close}-value should be higher than .05. In Structural Equating Modeling, standardized estimates correspond to measures of effect size. Cohen (1988) defines standardized coefficients around .10 as a small effect, around .30 as a medium effect and greater than .50 as a large effect.

Results

Means and standard deviations of the final scores for each task at each time point are given in Table 4.1. The first step was to explore the relationships between all tasks at the four time points (nine variables in total) with correlation analyses. Correlations between the nine variables are provided in Table 4.2. All correlations were significant, except for general language halfway through year one and early numeracy halfway through year two.

Univariate latent growth curve models

In order to investigate the development of general language and early numeracy separately, two univariate latent growth curve models were designed. This

Table 4.1 Descriptive statistics

	Halfway year 1		End year 1		Halfway year 2		End year 2	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Early numeracy	6.04	1.88	11.32	4.02	20.64	7.41	23.38	6.83
General language	43.44	10.08	48.01	11.22	54.88	9.18	62.13	10.27
Specific math language					16.92	3.01		

Table 4.2 Correlations between the tasks

	Task	1	2	3	4	5	6	7	8	9
1	Early numeracy H1	-								
2	Early numeracy E1	$.46^{**}$	-							
3	Early numeracy H2	$.27^{**}$	$.49^{**}$	-						
4	Early numeracy E2	$.32^{**}$	$.52^{**}$	$.60^{**}$	-					
5	General language H1	$.24^{**}$	$.28^{**}$	.06	$.22^{*}$	-				
6	General language E1	$.25^{**}$	$.37^{**}$	$.22^{**}$	$.32^{**}$	$.73^{**}$	-			
7	General language H2	$.34^{**}$	$.48^{**}$	$.30^{**}$	$.32^{**}$	$.51^{**}$	$.58^{**}$	-		
8	General language E2	$.34^{**}$	$.46^{**}$	$.33^{**}$	$.44^{**}$	$.43^{**}$	$.57^{**}$	$.75^{**}$	-	
9	Specific math language	$.30^{**}$	$.49^{**}$	$.44^{**}$	$.49^{**}$	$.46^{**}$	$.55^{**}$	$.53^{**}$	$.53^{**}$	-

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

methodological approach enables one to test for differences in developmental trajectories across time. In other words, with this analysis, the development of a skill is modeled by estimating the best growth curve for each child. In the current sample, data are obtained for each individual on four different occasions. Based on these four occasions, included in the model as observed variables (rectangles), the within-child growth trajectory is examined. To this end, the specified model includes two growth parameters (circles): the intercept ant the slope. The intercept reflects the height of the line, or, in terms of cognitive ability, the general ability of the child throughout the study. The slope reflects the average growth between time points. Both the intercept and the slope are estimated as latent variables, with the scores at each time point as observed indicators. The intercept does not change over time. Therefore, each indicator (i.e., observed variable) loads equally strongly on the intercept: loadings are fixed at 1. The slope exerts an increasingly larger influence on task scores at later time points, and therefore, these loadings also increase. The first loading on the slope factor was set at 0 and the last at 16, in accordance with the number of months between the first and fourth time point. The two loadings between these two time points were allowed to be estimated. By doing so, the slope was defined as the change from time point 1 to time point 4. That is, the mean of the slope was the mean difference between time point 1 and time point 4 (Muthén & Khoo, 1998).

The fit indices of the two separate univariate latent growth models are shown in Table 4.3 under univariate growth. In order to aid clarity, no separate figures of the univariate models are displayed. However, Figure 4.1 shows the multivariate growth model that will be discussed later. Despite a few minor differences due to combining the univariate models, the left side of this figure represents the first univariate model, the right side represents the second univariate model. The fit for the first univariate model, the early numeracy growth model, was good. There was no significant covariance between the intercept and slope. As a result, the covariance was fixed to 0, as is commonly done with non-significant relationships in Structural Equation Modeling. The residual variances of the observed early numeracy performances halfway through the first year (H1) and halfway through the second year (H2) were allowed to be freely estimated. However, the other two residual variances (E1 and E2) were constrained to be equal. This was done to correct for the difference in the versions of the early numeracy test between H1 and H2 (version A) and E1 and E2 (version B). The residual variance of the observed early numeracy performance halfway through the first year was not significant, and therefore, this variance was fixed to zero. The non-significant variance indicates that the residual error within the variable was fully accounted for by the paths specified in the model. The mean (M = 6.04, SE = 0.13, p < .01) and variance (M = 3.53, SE = 0.35, p < .01) of the intercept were both significant, indicating that children have an average level that is different from zero and they differ significantly from each

Table 4.3 Fit indices for univariate and multivariate growth models

	χ^2	*df*	*p*	*CFI*	*RMSEA*	p_{close}
Univariate growth						
Early numeracy	3.16	4	.53	1.00	.00	.73
General language	13.60	6	.03	0.97	.08	.15
Multivariate growth						
Early numeracy and general language	40.33	21	.01	0.96	.07	.16
Math language as mediator	62.92	27	.00	0.94	.08	.06

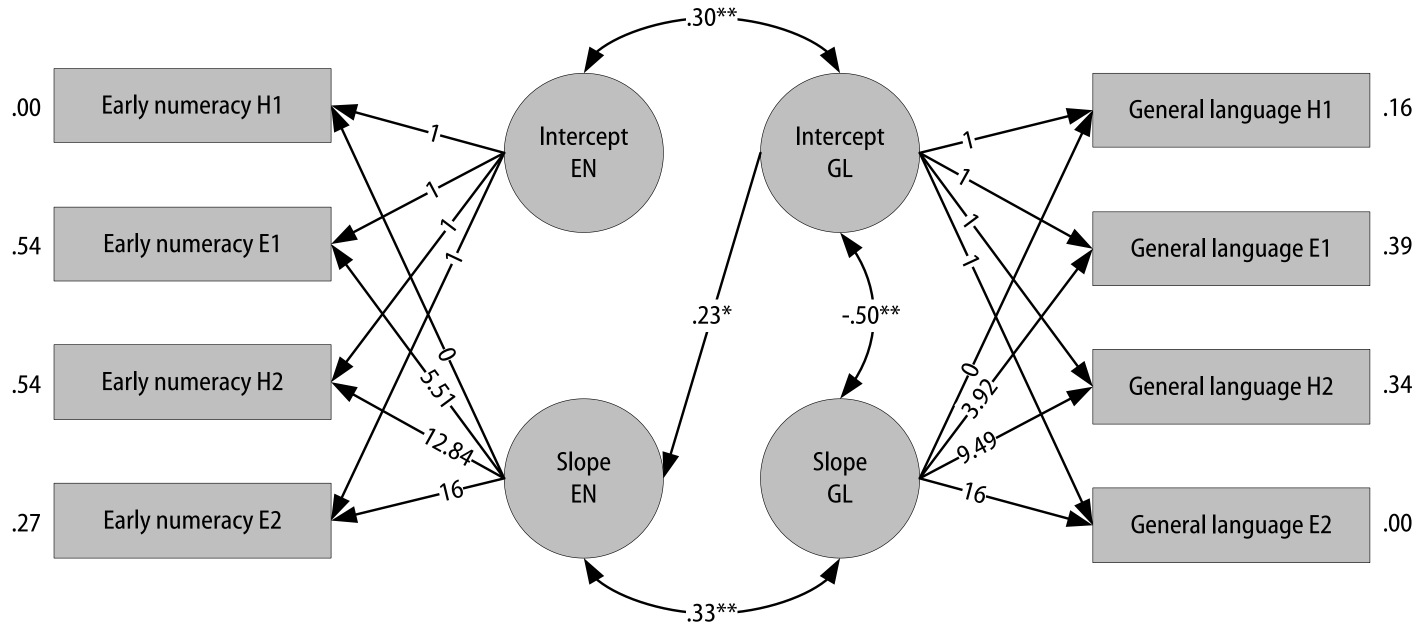

Figure 4.1 Growth model of early numeracy (left part), general language (right part), and the correlation between the two (middle part). ** $p < .01$, * $p < .05$, EN = early numeracy, GL = general language. *Note*. Factor loadings (above arrows) are un-standardized; explained variance (next to each rectangle) and (cor)relations between latent factors are standardized. To aid visibility, error terms are not displayed.

other in their average level. The mean (M = 1.11, SE = 0.07, p < .01) and variance (M = 0.12, SE = 0.02, p <.01) of the slope were also significant, meaning that children's early numeracy developed significantly during the time of the study and also differed from each other in this development.

The fit for the second univariate model, the general language growth model, was acceptable (see Table 4.3). Following the early numeracy growth model, the slope factors were fixed to 0, 4, 10 and 16, in accordance with the number of months between the measurements. The residual variance of the observed general language performance at the end of year two was not significant, indicating that children do not differ significantly in their language level at the end of the second year, and therefore, this variance was fixed to zero. Again, the mean (M = 43.20, SE = 0.76, p < .01) and variance (M = 84.72, SE = 11.29, p < .01) of the intercept and the mean (M = 1.14, SE = 0.06, p < .01) and variance (M = 0.43, SE = 0.06, p < .01) of the slope were significant. These values indicate that, first, children have an average language level that is different from zero and they differ significantly from each other in their average level, and, second, that the language proficiency of the children develops significantly during the time of the study and that children differ from each other in this development.

Multivariate latent growth curve models

In order to investigate the relationship between the growth models of general language and early numeracy, the two Univariate Latent Growth Curve Models were combined into one Multivariate Latent Growth Curve Model, presented in Figure 4.1. In this new model, the second and third slope factors of the language model were allowed to be estimated again. The relationship between early numeracy and general language was investigated by connecting the intercepts and slopes of the two growth models to each other. Furthermore, the intercept–slope regression to both sides was investigated. The numeracy-intercept to language-slope relation turned out to be negligible and non-significant and was, therefore, fixed at 0. The results in Figure 4.1 suggest that both the overall level of the child and growth during the 1.5 years of study in both early numeracy and general language were significantly related to each other. Both effects can be interpreted as medium effects. Furthermore, the initial status of general language of the children has a medium effect on the growth in early numeracy throughout kindergarten. This means that the higher the overall language level of a child, the higher the degree of development in early numeracy. In Table 4.3, under multivariate growth, the fit indices are presented. It can be concluded that the model has a good overall fit.

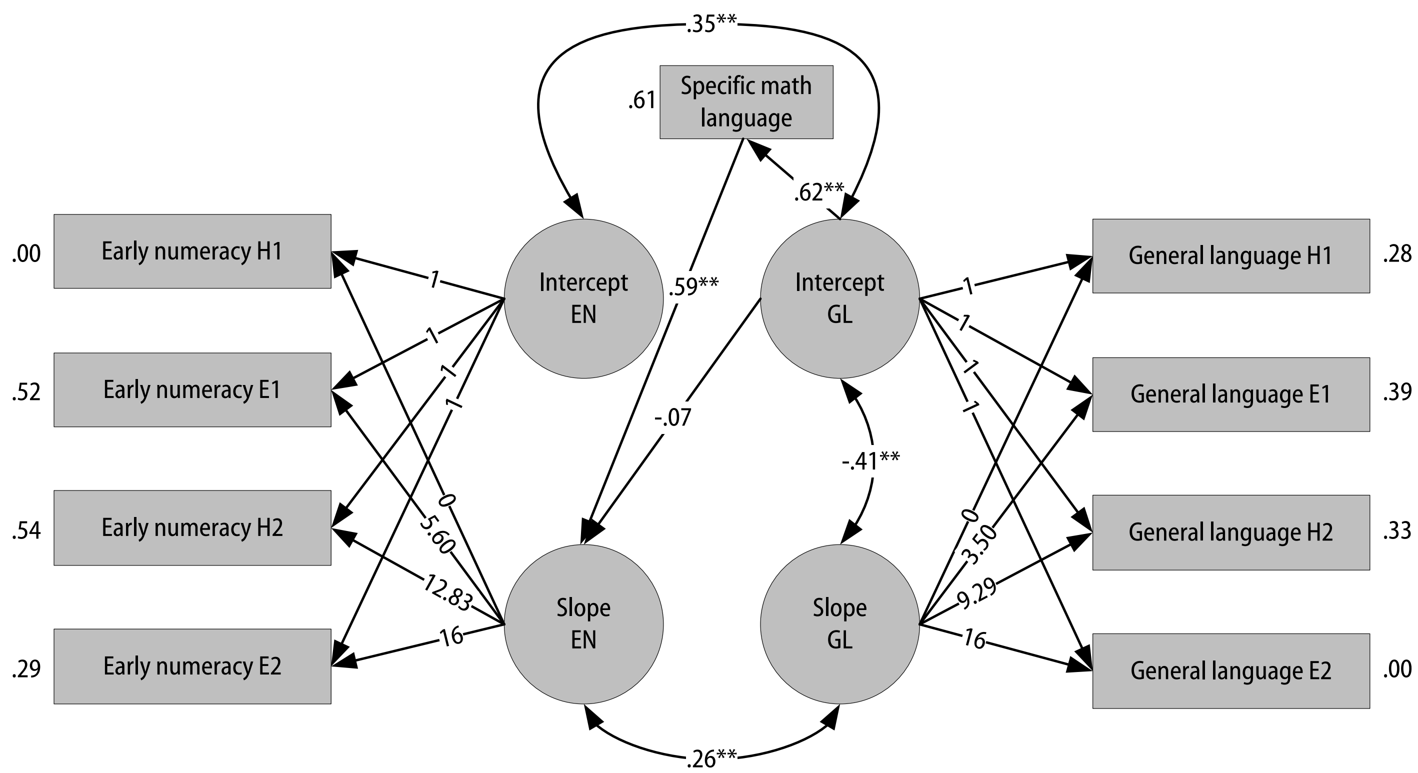

Figure 4.2 Multivariate growth model of early numeracy and general language with specific math language as mediator. ** $p < .01$ *Note*. Factor loadings (above arrows) are un-standardized; explained variance (next to each rectangle) and (cor)relations between latent factors are standardized. To aid visibility, error terms are not displayed.

Final model

The next aim of the study was to investigate whether specific math language mediates the relationship between general language and early numeracy. Therefore, specific math language was added to the previous multivariate model as a covariate that affects early numeracy growth and is affected by the intercept of general language. After omitting all non-significant paths, the fit of the model was good (see Table 4.3). The model is displayed in Figure 4.2. The only non-significant effect that remained was the effect of the general language intercept on early numeracy growth, making it possible to test the indirect effect of general language via specific math language on early numeracy growth. The significance of specific language as an intervening variable was evaluated using the delta method (MacKinnon, 2008). The indirect effect turned out to be significant ($\beta_{indirect}$ = 0.37, SE = .08, p < .01). Specific math language served as a mediating variable between the intercept of general language and the slope of early numeracy. 39.0% of the variance in specific math language was accounted for by the intercept of general language, while 30.9% of the variance in early numeracy growth was accounted for by specific math language. Both effects can be interpreted as large. The model shows, furthermore, that the covariance between the intercept of early numeracy and the intercept of general language remained medium, as well as the covariance between the slope of early numeracy and the slope of general language.

Conclusion and discussion

The aim of the present study was to clarify the developmental relationships between general language, specific language and numeracy within kindergartners with low early numeracy at risk for developing later mathematical learning difficulties. Regarding the first research question, focusing on the existence of a mutual relationship between language development and early numeracy development in kindergartners with (very) low early numeracy, it can be concluded that the initial status of both skills, as well as the growth rate, are interrelated and influence each other reciprocally. The initial status of general language affects early numeracy development throughout kindergarten. This is in line with previous studies suggesting that language ability is a prerequisite for learning early mathematical skills (e.g., Aiken, 1972; Duncan et al., 2007; Kleemans et al., 2011a). Most of these previous studies have ascribed this relationship to certain specific language terms that might facilitate the use of numerical concepts (Gelman & Butterworth, 2005; Halberda et al., 2008; Sarnecka & Gelman, 2004). The second research question tested whether specific math language mediates the relationship between general language development and early numeracy in kindergartners with (very) low early numeracy. The present results confirm the hypothesis that specific math language is an intervening variable within the developmental relation between general oral language and early numeracy, and states the importance of specific math language in early numeracy which is congruent with the findings of Lansdell (1999). This finding also contributes to the idea that some children experience particular difficulties in the language of mathematics (Ginsburg, 1972; Schleppegrell, 2010).

Although the results of this study clearly support the idea that specific math language should be understood when learning early numerical skills, four limitations of the present study need to be taken into account. The first limitation addresses the cut-off score. The selection criterion in the present study (< the 15th percentile) was deliberately chosen based on previous research (Desoete et al., 2004; Seethaler & Fuchs, 2010) and can be understood as strict. Nevertheless, other studies use a cut-off score of two standard deviations below the mean to diagnose a more specific group of children with poor early math skills (e.g., Desoete et al., 2004) instead of low achieving kindergartners. The difference between the cut-off scores should be taken into account when directly comparing the results of different studies. Another limitation focuses on the mean age of the selected children. Because their age was significantly lower than the mean age of the unselected children, it must be reckoned that some of the children may have been behind because they were younger. In addition, only one score on specific math language was available to reflect the best overall level of specific math language, while general language and early numeracy were measured four times throughout the study. It would have been very informative to also include a growth rate of specific math language in the performed analyses. However, due to the time restraints of including four measures, this was not feasible. The final limitation is related to the measures for language and early numeracy. The present study focuses on both general oral language and early numeracy as an overall ability consisting of a combination of several specific language or numeracy skills. Of course, it can be argued that splitting the abilities into specific constructs, such as grammatical ability and vocabulary in oral language (Storch & Whitehurst, 2002) and verbal and non-verbal abilities in early numeracy (Kleemans et al., 2011a), would be meaningful. However in this study, no attempt was made to operationalize different constructs within the language or numeracy ability in order to stay as close as possible to the way language and numeracy ability is measured within an educational setting in Dutch kindergartens (Lansink, 2009; Van Luit & Van de Rijt, 2009). Yet, it would be highly interesting to find relations for specific constructs. The findings of the present study call for further studies into the developmental relationship between the different subcomponents of language and early numeracy in children at risk for math learning disabilities and whether specific language mediates all of these relationships or only partly.

Another recommendation for future research is to apply a similar design to older children diagnosed with developmental dyscalculia. Since Butterworth, Varma, and Laurillard (2011) suggest that there are children with developmental dyscalculia with normal language development and no deficits in other cognitive areas, but lack an intuitive grasp of number specific weaknesses in numeracy, a similar design with older children with dyscalculia enables an examination into whether children with dyscalculia also have trouble with specific math language.

Behavioral and anatomical evidence from previous studies suggest that arithmetic and language comprehension are mediated by partially overlapping brain networks (e.g., Baldo & Dronkers, 2007). As a result, another interesting subject for further studies would be to identify other underlying factors that can explain both language and early numeracy, such as processing time (e.g., Berg, 2008), attention (e.g., Swanson, 2011), and working memory (Passolunghi & Lanfranchi, 2012).

These conclusions raise several implications. Currently, measuring general language achievement is part of the curriculum in a substantial number of preschools and kindergartens, but because these instruments are insufficient for identifying difficulties that can influence early numeracy development and the origin of math learning difficulties, designing a more specific test on specific math language could be highly valuable. The present study revealed quantity concepts, such as “more,” “less” and “equal,” and spatial concepts, such as “below,” “behind” and “above,” as important specific math language. Besides testing these concepts, the importance of learning specific math language should be acknowledged more within the educational setting; in other words, it should be more systematically included and embedded within the curriculum. Practitioners searching for guidelines can find a comprehensive list of math language in the vocabulary list provided by the Department of Education and Employment (2000).

Therefore, an implication following these conclusions is the emphasis on specific math language in education to children with low early numeracy. Favorable circumstances to provide at-risk children optimal opportunities to improve their knowledge and skills of specific math language include use of clear language by the teacher, meaningful practice in 'every-day situations,' and continuous verification on whether children understand the offered language correctly through informal observations rather than formal assessments. Following Lansdell (1999), there are a few recommendations for teachers to avoid serious misunderstandings in children's learning of this math language including the awareness of 'ambiguous' words, the consciousness and consistency of their own language use, assessments for children's understanding of new concepts, and introduction of new meaning in context once the concepts are understood.

Given that the results in the present study reveal specific math language as a predictive factor in early numeracy growth of at-risk kindergartners, they provide a promising target for future intervention studies. While recently conducted studies show an effect of an early numeracy intervention targeting a small-group of high-risk kindergartners, on both number competencies and general math achievement (e.g., Bryant et al., 2011; Fuchs, Powell, et al., 2010; Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012; Toll & Van Luit, 2012), as well as storybook reading affecting early numeracy skills (Anderson, Anderson, & Shapiro, 2004; Young-Loveridge, 2004), it would be highly advisable to integrate the effective aspects of early numeracy and early language programs into a remedial intervention for children at risk for math learning difficulties which aims to support both numerical skills as well as specific math language. This implication supports the notion of Jeon and colleagues (2011) highlighting the importance of early intervention for at-risk children to enhance their school readiness skills, including their language and numeracy abilities. Together, the results show the importance of teaching young at-risk children how to connect specific math language to early numeracy skills in kindergarten.

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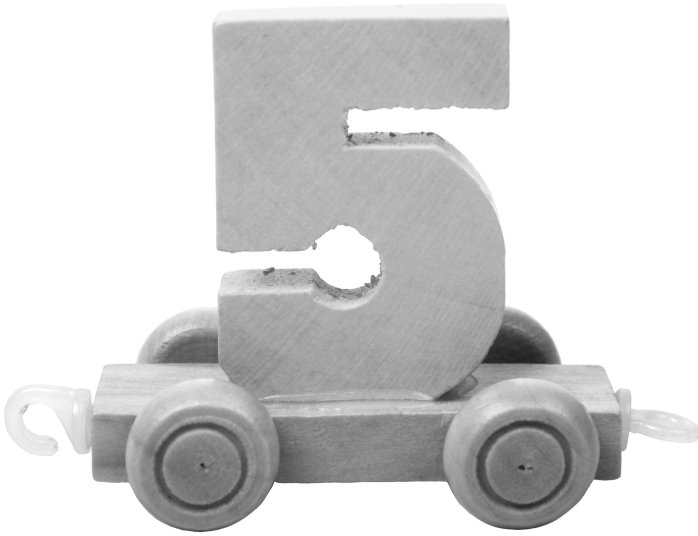

Early numeracy intervention for low-performing kindergartners

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Abstract

Early numeracy in kindergarten has proven to be a strong predictor of mathematical achievement. The aims of this study were to test the effectiveness of a remedial numeracy program for children who were low-performing and to evaluate the role of visual and verbal working memory in the development of numeracy. The study included 196 kindergartners. The children with a pretest numeracy score falling below the 50th percentile were matched and randomly assigned to an intervention group and a control group. The intervention group obtained meaningful and statistically significantly higher adjusted outcome numeracy scores at the posttest stage than did the control group. This result, however, was not found among the group of children falling below the 25th percentile at the pretest stage. Verbal working memory, but not visual working memory, might best account for differences in the growth measured within the intervention group.

Introduction

Research has shown that young children develop a relatively powerful everyday sense of mathematics or early numeracy before beginning primary school (Clements & Sarama, 2007). Most children already have a spontaneous and sometimes explicit interest in numerical ideas. By the end of the preschool years many children have a solid if not yet fully mature understanding of counting concepts, even without formal instruction (Geary, 2000). For most children, learning these skills is a natural process that is guided by informal learning which occurs in the home (e.g., Ginsburg, Lee, & Boyd, 2008). Not all children, however, develop this informal knowledge. By the age of five, children have thus demonstrated wide individual differences in their early numeracy knowledge (e.g., Aunio, Hautamäki, Sajaniemi, & Van Luit, 2009; Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). Research has shown socioeconomic status (SES) to be a key factor explaining these individual differences (e.g., Jordan, Kaplan, Ramineni, & Locuniak, 2009). Individual differences in initial numeracy knowledge appear to have significant short-term and long-term consequences (Aubrey & Godfrey, 2003; Jordan, Glutting, & Ramineni, 2010; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Kavkler, Aubrey, Tancig, & Magajna, 2000; Locuniak & Jordan, 2008). In the short-term – during the primary school career of the child – deficient early numeracy skills can interfere with the later acquisition of math skills (Schopman & Van Luit, 1996). Children with weak basic numeracy skills might not develop the conceptual structures required to support the learning of advanced mathematics (Van Luit & Schopman, 2000). Early numeracy is repeatedly proven to be a strong predictor of growth in math achievement – for example, the growth between first and third grade, as well as achievement through third grade (Jordan et al., 2009).

Several studies have shown that children with lower numeracy scores in kindergarten are at risk of developing math-related learning difficulties in primary school (e.g., Gersten, Jordan, & Flojo, 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Mazzocco & Thompson, 2005; Morgan & Farkas, 2009). Stock, Desoete, and Roeyers (2009), as well as Toll, Van der Ven, Kroesbergen, and Van Luit (2011) have investigated the extent to which it is possible to predict a child will experience persistent math-related difficulties based on their early numeracy skills as measured in kindergarten. Eight-seven percent and 77% of children with math-related disabilities at age 7 or 8, respectively, were correctly identified as being at risk in kindergarten of developing math learning difficulties (Stock et al., 2009; Toll et al., 2011). Some studies, moreover, have identified a relationship over a longer time span. McClelland, Acock, and Morrison (2006), for example, have shown that learning-related early numeracy skills present at kindergarten-age uniquely predict math skills between kindergarten and sixth grade, after researchers controlled for intelligence, age, ethnicity and maternal education level.

The role of working memory

Literature on early numeracy has shown a recent focus on working memory (e.g., Kyttälä, Aunio, & Hautamäki, 2010). Working memory refers to the ability to both store and manipulate information simultaneously (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Just & Carpenter, 1992). It is also understood, more precisely, as the ability to store information temporarily and revise it with new incoming information. In research on working memory, the multi component model initially proposed by Baddeley and Hitch (1974) remains useful. The model is comprised of an attention control system – the 'central executive' – which is aided by two subsidiary slave systems – the 'phonological loop' and the 'visuospatial sketchpad'. A third slave system – the 'episodic buffer' – subsequently added to the model is assumed to be a limited-capacity temporary storage system capable of integrating information from a variety of sources (Baddeley & Hitch, 2000). The basic modular structure of working memory has proven to be stable and measurable by the time a subject reaches the age of four (Alloway, Gathercole, Kirkwood, & Elliott, 2008; Gathercole, Pickering, Ambridge, & Wearing, 2004). Alloway, Gathercole, and Pickering (2006) also explored the structure of verbal and visuospatial short-term and working memory in young children, and created a two-factor model in which a distinction is made between a storage component (i.e., holding information available for a certain period of time)and an updating component(i.e., storing information for a certain period of time and revising this information in the light of new information); a further distinction has been made between verbal and visual working memory, as well.

Working memory has been hypothesized as underpinning a range of higher-order cognitive abilities, including mathematics and early numeracy (e.g., Vukovic & Siegel, 2006), and is considered important for such performances because incoming information must be stored and manipulated during numerical problem solving (Raghubar, Barnes, & Hecht, 2010). An increasing number of studies have confirmed the strong connection between working memory and mathematics performance in first and second grade (e.g., De Smedt et al., 2009; Passolunghi, Mammarella, & Altoè, 2008; Toll et al., 2011), and also between working memory and (weak) early numeracy skills in kindergarten specifically (e.g., Espy et al., 2004; Kroesbergen, Van de Rijt, & Van Luit, 2007; Kyttälä et al., 2010). Results show the importance of identifying working memory characteristics in the early development of numeracy cognition (Klein & Bisanz, 2000), but there is no consensus whether verbal or visual working memory is a better predictor of numeracy development, since both components of working memory have been repeatedly related to numeracy achievement and development (Raghubar et al., 2010). Both components are included in the present study, in order to investigate the extent to which working memory is related to early numeracy development.

Opportunities and challenges for intervention

Supporting numeracy-related learning among children 3 to 5 years old has a positive effect on the lives of these children for many years thereafter (Clements & Sarama, 2011). Within the field of scientific education, several studies have examined the effectiveness of numeracy interventions designed for children in kindergarten. Some of these studies have focused on at-risk children from low-economic status families in particular (Baroody, Eiland, & Thompson, 2009; Dyson, Jordan, & Glutting, 2011), on children attending special education (Van Luit & Schopman, 2000), and on children with early numeracy ability below a certain criterion-score on an early numeracy test (Van de Rijt & Van Luit, 1998). The results of these studies have confirmed the importance of effective numeracy instruction and of receiving additional assistance and instruction in kindergarten – particularly for children with low early numeracy performance.

Empirical evidence centers around curricular interventions implemented over the long-term, such as Building Blocks (Clements, Sarama, Spitler, Lange, & Wolfe, 2011), Big

Math for Little Kids (Greenes, Ginsburg, & Balfanz, 2004), and Mengen, Zählen, Zahlen (Krajewski, Nieding, & Schneider, 2008). Studies have also shown that extra-curricular activities can stimulate different domain-specific skills to support the early numeracy skills of kindergartners. Siegler and Ramani (2009), for example, found positive results for improving numerical representations by playing linear board games, based on the idea of Siegler and Booth (2005) that studying number line estimation is a useful means for learning about early numeracy because both require approximating magnitudes. The results of other studies, furthermore, have provided evidence that promoting the type of early abstract thought as is involved in the oddity principle (i.e., the ability to identify the only item in a group that differs from all others along some dimension), seriation (i.e. arranging things in order by size or some other ordinal dimension), and conservation (i.e., the understanding that the number of items in a group cannot change unless one or more is added or subtracted) can enhance kindergartners' numeracy abilities (e.g., Pasnak et al., 2009).

Extensive evidence from experimental and educational studies of children developing typically supports the idea that numeracy ability is not unidimensional, but is instead comprised of several components (Dowker, 1998; Ginsburg, 1977). In intervention studies spanning multiple domains of numeracy (e.g., Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005; Krajewski et al., 2008), a combination of skills necessary for preparatory math education were offered in order to cover the complete domain of early numeracy. Based on extant literature, however, it is not clear how many domains or subareas can be distinguished. In the present study, early numeracy is defined as nine domains: (1) math language, including ordinal and position words such as "under," "above," "before," and "after" (Kleemans, Segers, & Verhoeven, 2011; Schleppegrell, 2010); (2) reasoning skills, such as classification, comparison and seriation (e.g., Pasnak et al., 2009); (3) verbal counting skills, such as acoustic counting and skip counting (Fuchs et al., 2010; Threlfall & Bruce, 2005); (4) concrete counting skills (i.e., counting tangible quantities), such as synchronic counting and resultative counting (Askew, Bibby, & Brown, 2001; Gelman, 2008); (5) structures, such as a dice structure or a tally mark method (Andres, Di Luca, & Pesenti, 2008; Case et al., 1996; Dehaene, 1992; Rips, Bloomfield, & Asmuth, 2008); (6) recognizing and naming the number symbols (Zhou & Wang, 2004); (7) measuring and geometry (Clements & Sarama, 2011); (8) knowledge of the number line, such as the ability to estimate the relative position of a number on a linear line (Aunio, Hautamäki, & Van Luit, 2005; Siegler, 2009); and, (9) simple calculations (Carruthers & Worthington, 2004).

Along with the identification of different domains to be included within the content of an effective early numeracy intervention program, educational research on early numeracy has revealed a number of challenges that should be taken into account when offering early numeracy instruction to kindergartners. The first challenge is to identify an effective instruction method that can be followed by the teacher, and can be adapted to the needs of the individual child. This is important because adaptive instruction at an early stage is key for effective classroom practice (Akos, Cockman, & Strickland, 2007; Kerry & Kerry, 1997; Levy, 2008). Research has shown SES to be an important factor in explaining such differences (e.g., Jordan et al., 2009). For most children with special educational needs, direct instruction is most effective (Kroesbergen & Van Luit, 2003). Direct instruction, however, has not been integrated into all early numeracy programs.

A second challenge focuses on the language involved in executing numeracy-related tasks. Math-related language – including both number words and math-related concepts such as "more," "less," "higher," and "lower" – facilitates the use of numerical concepts (Gelman & Butterworth, 2005), and research has shown some children have particular difficulties with the language of mathematics (Ginsburg, 1972; Kleemans et al., 2011; Schleppegrell, 2010). Such math-specific language should be explicated and integrated in a numeracy program for kindergartners (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006).

The third challenge relates to the manner in which children learn to map concrete quantities to more abstract number symbols. For low-performing kindergartners in particular, learning to relate a tangible amount of objects to a specific written symbol is not an obvious connection. The ability to relate quantities to symbols, however, is necessary for performing more advanced mathematical tasks. According to the action theory, internalizing mental number knowledge should happen on three levels; concrete, semi concrete, and abstract (Pape & Tchoshanov, 2001).

The present study

A growing body of research has focused on the effectiveness of early numeracy intervention involving kindergartners achieving at typical levels (e.g., Kaufmann et al., 2005; Krajewski et al., 2008). However, fewer attempts have been made to specifically include kindergartners performing below average or scoring very low on early numeracy measures.

Previous research, furthermore, has identified the predictive relationship between working memory and early numeracy or counting abilities (Bull, Espy, & Wiebe, 2008; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Mabbott & Bisanz, 2008; Passolunghi et al., 2008; Passolunghi, Vercelloni, & Schadee, 2007; Schuchardt, Maehler, & Hasselhorn, 2008). Insofar as research on the topic has been conducted, the role of working memory and the effect of early numeracy intervention have not been studied in a cohesive research design. The present study therefore followed an experimental design which examined the effect of a specific early numeracy intervention, “The Road to Mathematics” (TRTM; Van Luit & Toll, 2013), and also accounted for working memory skills of the children prior to the intervention. TRTM is especially designed for kindergartners scoring below average by meeting the challenges in early numeracy education. Children scoring below the 50th percentile on a national standardized numeracy test were, in principle, the target group of TRTM and were thus qualified for the intervention in this study. For the purpose of the study, however, a subgroup was formed out of this larger population, to act as a specific target group. This subgroup was comprised of those children scoring particularly low on the early numeracy test – below the 25th percentile – as these children are at the greatest risk of developing math-related learning difficulties in primary school (e.g., Gersten et al., 2005; Jordan et al., 2006; Mazzocco & Thompson, 2005; Morgan & Farkas, 2009).

The following research questions were addressed:

1. Is the TRTM remedial program an effective intervention regimen to support the early numeracy development of all children with early numeracy ability below average (below the 50th percentile), of children with early numeracy ability below average (25th–50th percentile) and of children with very low early numeracy ability (below the 25th percentile)?
2. To what extent is working memory related to early numeracy development among children with early numeracy ability below the 50th percentile within the intervention group?

Method

Participants

The participants were 196 kindergartners (M_{age} = 5.23 years, SD_{age} = 4.37 months, 100 boys, 96 girls) in their second year of kindergarten.[1] A power analysis for an ANCOVA with three groups and three covariates was performed, with α = .05; a medium effect

1 In the Netherlands, children begin attending kindergarten when they reach the age of four. They attend, on average, two years of kindergarten before moving to first grade in September of the year in which they turn six years old.

size, $r = 0.3$; and a desired power of 0.80 (Cohen, 1992). This resulted in a required overall sample size of 111 students. Four children moved while the study was ongoing and their results were subsequently excluded from further analyses, resulting in a complete data set for an adequate sample size of 192.

The children were drawn from six Dutch primary schools representing two of the twelve Dutch provinces. Parental consent was obtained for all children who participated in this study. All children were administered the 45-item standardized Early Numeracy Test-Revised (ENT-R; Van Luit & Van de Rijt, 2009) during the pretest stage. The scores were converted to norm scores based on the age of the children. Those children with norm scores falling below the 50th percentile on this test ($N = 98$) were paired with another student in their school with a comparable pretest norm score, and the coupled children were then randomly assigned to either the Intervention Group (IG; $N = 52$) or the Control Group (CG; $N = 46$). This random assignment was made at the school level, leading to inconsistent group sizes across the sample. Within the IG and CG groups, respectively, a distinction was drawn between children who scored above or below the 25th percentile. The children with a score above the 50th percentile on the ENT-R constituted the Typically-Achieving Group (TAG; $N = 94$), named hereafter as the "reference group."

Descriptive statistics of the three groups defined above and of the two specific target groups within the IG and CGare presented in Table 5.1. The dichotomous variable SES was based on a classification system developed by the Dutch government that provides primary schools with special budget considerations for children from a low

Table 5.1 Descriptive group statistics and pretest early numeracy score for three groups and specific target groups (25th–50th and 0th–25th) within the IG and CG

	N	Sex		SES		Age (months)		EN score pretest	
		Boys (%)	Girls (%)	High (%)	Low (%)	*M*	*SD*	*M*	*SD*
IG	52	26 (50.0)	26 (50.0)	32 (61.5)	20 (38.5)	61.79	4.06	12.85	3.48
25th–50th	27	13 (48.1)	14 (51.9)	16 (59.3)	11 (40.7)	62.68	4.53	14.93	2.73
0th–25th	25	13 (52.0)	12 (48.0)	16 (64.0)	9 (36.0)	61.14	3.79	10.19	2.52
CG	46	24 (52.2)	22 (47.8)	27 (58.7)	19 (41.3)	61.98	4.23	12.89	3.52
25th–50th	25	8 (32.0)	17 (68.0)	16 (64.0)	9 (36.0)	62.30	5.16	15.16	2.48
0th–25th	21	16 (76.2)	5 (23.8)	11 (52.4)	10 (47.6)	61.24	2.37	10.60	2.75
TAG	94	49 (52.1)	45 (47.9)	72 (76.6)	22 (23.4)	63.63	4.38	22.34	4.96

Note. EN = early numeracy, IG = intervention group, CG = control group, TAG = typically achieving group.

socioeconomic background. The classification divides children into three weight groups, largely based on parental education. A weight of zero indicates at least one parent attended higher secondary education or above; a medium weight means the highest education of both parents was lower secondary education; and high weight means the highest education of one of the parents is primary school or (secondary) special education. In this study, children with no weight were labeled high SES and children with a medium or high weight were labeled low SES.

Measures

In total, five individual tests were administered during both the pretest and posttest stages.

Early Numeracy Test-Revised. Early numeracy skills were measured with the ENT-R (Van Luit & Van de Rijt, 2009), which assesses math prerequisites, counting, and estimation skills. The test consists of nine components: concepts of comparison, classification, correspondence, seriation, using numerals, synchronized and shortened counting, resultative counting, general understanding of numbers and estimation. Each component contains 5 items. There are two versions of the test, version A and version B. The reliability coefficient of both versions have been shown to be $\alpha = .94$ (Van Luit & Van de Rijt, 2009). Internal consistency based on the data in the present study was $\alpha = .82$ for version A and $\alpha = .83$ for version B. No comparable tests with regard to content and psychometric properties are available in the Netherlands, so it is not possible to evaluate the construct validity of the instrument. The judgments of experts, correlations, results of factor analyses, and results of the Item Response Theory nevertheless show that the instrument measures early numeracy (Van Luit & Van de Rijt, 2009).

At the pretest stage, children were randomly administered either version A or B; the child completed the other version at the posttest stage. The raw score was converted into a norm-based percentile score (range = 0–100), to determine which children fell below a norm score of 50 and were, thus, qualified for the intervention. For subsequent analyses, the raw score of a child (range = 0–45) was used.

Automated Working Memory Assessment. Working memory ability was measured via four computer-based tasks drawn from the Automated Working Memory Assessment (AWMA; Alloway, 2007) – Dot Matrix, Odd One Out, Word Recall Forward, and Word Recall Backward. The AWMA was translated and voice-recorded from its original English into Dutch. The AWMA has evidence of concurrent validity with the WISC-IV Working Memory Index and good diagnostic validity for children with low working memory skills (Alloway et al., 2008). For children ages 4.5 to 11.5, the test–retest reliability of the four tasks has been shown to be 0.83, 0.81, 0.76, and 0.74, respectively (Alloway et al., 2008). In the present study, the internal consistency of the tasks was 0.74, 0.77, 0.72, and 0.69, respectively. All tasks were preceded by a brief practice session and were adaptive because the task automatically terminated when a child gave three incorrect answers within a set of items of the same length.

First, the capacity of visuospatial storage component was assessed with *Dot Matrix*. The children were presented with a 4 x 4 matrix on the computer screen. A red dot appeared briefly in one of the boxes and children had to point out the correct box. The test started with a level with one dot in the matrix, building up to a level with a sequence of seven dots presented across the matrix. Each level consisted of six trials; a trial was counted as incorrect when one of the boxes was omitted, when the sequence of boxes selected was incorrect, or when a box was recalled incorrectly. When the first four trials within a level were recalled correctly, the child proceeded to the next level. The possible range of scores was 0 to 28.

Second, the visuospatial processing component was measured by the *Odd One Out* task, in which children were asked to point out the odd shape in a row of three geometrical shapes, and to remember the consecutive locations of these shapes in sets of increasing lengths. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The possible range of scores was 0 to 28.

Third, the verbal storage component was assessed with the *Word Recall Forward* task, in which a recorded voice provided a series of semantically unrelated words, after which the child was asked to repeat the words in the same order. The string of words became progressively more extensive as the child accurately recalled several strings. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The possible range of scores was 0 to 24.

Fourth, the verbal processing component was assessed with the *Word Recall Backward* task, in which a recorded voice provided a series of semantically unrelated words, after which the child was asked to repeat the words in reverse order. The string of words became progressively more extensive as the child accurately recalled several strings. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The possible range of scores was 0 to 24.

Each of the four working memory tasks in the present study represents a component of the model of Alloway et al. (2006). To confirm this model, Confirmatory Factor Analysis (CFA) was performed using structural equating modeling (SEM) on the four working memory tasks from both the pretest and posttest stages, resulting in a model with two latent factors – visual and verbal working memory – with each latent factor having two indicators, based on the distinction drawn by Alloway et al. (2006). This two-factor model was deemed applicable with a good fit (Pretest: $\chi^2(1) = 1.35$, $p = .25$, $CFI = 1.00$, $RMSEA = 0.04$, $P_{close} = .35$, $AIC = 3274.60$; Posttest: $\chi^2(1) = 0.30$, $p = .58$, $CFI = 1.00$, $RMSEA = 0.00$, $P_{close} = .66$, $AIC = 3384.18$) The standardized factor loadings from the best fitting two-factor model for the pretest scores presented in Table 5.2 were used to compute the individual factor scores on visual and verbal working memory that were used in subsequent analyses.

Procedures

The design of the study followed a pretest–intervention–posttest sequence. The posttest stage was administered between one and three weeks after the last intervention session. The individual measurements collected as part of the pretest and posttest stages, respectively, were administered by several trained assistants, each having earned at least a Bachelor's degree in education, special education, or child psychology. Each assistant received three hours of training on the instruments and then administered a trial test session with a child, on which they received feedback.

One week after the pretest stage, the 8 week intervention period began. The intervention group was taught the TRTM remedial program and the children from the CG and TAG attended the regular curriculum over the same period. All groups received numeracy education for approximately 1 hour per week. The content of the regular curriculum was designed to follow an early numeracy curriculum for kindergarten. Three different curricula were offered in the schools, referred to as "Wizwijs," "Schatkist," and "Leerlijnen Wiskundige Oriëntatie." "Wizwijs" covers three domains (numbers and

Table 5.2 Standardized factor loadings CFA for the pretest scores

		Stand. Fact. Loading (*SE*)	Intercept (*SE*)	Residual variances (*SE*)	Correlation (*SE*)
Visual WM	Dot Matrix	.40 (0.10)	3.44 (0.19)	.84 (0.08)	
	Odd One out	.85 (0.18)	2.63 (0.15)	.27 (0.31)	.57** (0.15)
Verbal WM	Word Recall Forward	.51 (0.10)	7.36 (0.39)	.74 (0.10)	
	Word Recall Backward	.67 (0.11)	1.61 (0.11)	.56 (0.15)	

Note. WM = working memory. ** $p < .01$.

calculations, measuring and sizes, and geometry), and "Schatkist" covers to six domains (time, space orientation, comparison, classification and seriation, measure and weigh, counting and quantities. Throughout, all schools attempted to comply with the Dutch kindergarten objectives regarding "early numeracy" (Gelderblom, 2007; Treffers, Van den Heuvel-Panhuizen, & Buys, 1999).

The TRTM program (Van Luit & Toll, 2013) was offered in 16 approximately 30 minute sessions, administered twice a week. The intervention sessions took place outside the classroom, in small instruction groups of three to four children each. The sessions were guided by four trained supervisors, each of whom was responsible for 3 to 4 groups. All supervisors had at least a Bachelor's degree in education, special education, or child psychology, and each received four hours of training, including background, theory, task-practicing, and role-playing. The supervisors completed a standardized evaluation form immediately after each session, which included questions pertaining to task feedback (i.e., "Please provide feedback about the level of appreciation the children showed toward this task") and child observation (i.e., "Please judge each child's execution of this task on a scale from 1 (very low) to 5 (very high)"), and were also observed by one of the authors once every two weeks.

Since the effectiveness of an intervention strategy can only be tested when its presence is comparable for all participants (Leff, Hoffman, & Gullan, 2009), data were monitored to determine that children attended at least 8 sessions, or 50% of sessions. The mean attendance of the children was 14.73 sessions (SD = 1.52; range = 9–16). Minimum attendance was 9 sessions (one child); 21 children attended all 16 sessions, 17 children 15 sessions, 4 children 14 or 13 sessions, and 5 children 12 sessions. Because no statistically significant correlation (Pearson's p = .16, p = .26) was found between the attendance and difference score between early numeracy pretest and posttest, it was assumed that attendance was comparable for all participants.

TRTM aims to teach low-performing kindergartners a range of basic numerical concepts and math-related language, provide to them the meaning of numbers through structured activities, and therefore simplify the transition to math education in first grade. TRTM addresses a wide range of skills, and in doing so offers children a foundation upon which they can build as they enter into first grade. In line with other interventions that cover several aspects of early numeracy, nine different numeracy domains have been integrated into the program: math language, reasoning skills, verbal counting, concrete counting, structures, number symbols, measuring, number lines, and simple calculations. An explanation of how these seven domains are operationalized into subsidiary skills and addressed through TRTM is provided in Table 5.3.

Table 5.3 Domain overview, operationalization in sub skills, and tasks for the domains of the early numeracy program in the present study

Domain	Sub skills	Tasks example
Math language	Number words, ordinals, position words, comparisons	Children represent a rhyme about little mousses playing hide-and-seek
Reasoning skills	Comparison, classification, correspondence, seriation	Children classify and seriate their shoes in multiple ways; by size and color
Verbal counting	Acoustic counting and skip counting (2, 4, 6, ..)	The children practice their counting skills forwards and backwards with songs, rhymes, counting together or counting alone
Concrete counting	Synchronic, resultative counting, and counting on (5, 6, 7, ..)	The children practice their counting strategies while counting tangible objects or their fingers
Structures	Fingers, tally marks, dice, number symbols up to 20	The children play bingo games with (flash) cards and dices and number cards, or collect cards of all possible amounts (1 to 5)
Number symbols	Recognizing and naming the number symbols	The children play games with (flash) cards, or a number coloring game or a number connection game
Measuring	Comparison, estimations of distances, shapes	Children play puzzle games with shapes or try to estimate the number of steps to a specific object
Number lines	Position of numbers, difference between numbers, relation between numbers, estimation	Children walk a number tile path, estimate where a tile must lay between 1 and 20, determine the 'neighbors' or missing tile and play a game
Simple calculations	Addition, subtraction	Children play a game in which a rover that takes away or set a number of concrete objects

The version of TRTM used in this study consisted of 16 sessions with complete instructional plans and accompanying materials. Each session was divided into three separate tasks, resulting in 54 tasks total. Most tasks were designed to address multiple program domains, and each of the nine domains (math language, reasoning skills, verbal counting, concrete counting, structures, number symbols, measuring, number lines and simple calculations) were addressed in at least five tasks.

Based on previous research, TRTM is characterized by three primary features. The first feature is the importance of math-related language. Within TRTM, a distinction is made between "math language" (words that are necessary to perform math problems and calculations, such as "one," "more," "less," or "higher"), and "instruction language" (language which is necessary to complete the concerned task in an acceptable manner or to explain an adequate solution, or "strategy" to a problem, for instance "in-a-row" or "one-by-one"). The relevant math and instruction language for each task was highlighted in a separate frame on the instructional plan, so that the supervisor could use the specific to-be-learned terms extensively in an effort to elicit the same language from the children.

The second feature of TRTM is the importance of instruction. All of the program tasks were presented to the children through two different instruction steps for each task: learning by doing and structure facilitation (e.g., Aleven & Koedinger, 2002; Norris & Ortega, 2001). In the first step, children are exposed to learning by doing, also referred to as "learner-centered instruction." The teacher has a guiding and stimulating role, and asks open-ended questions. Only when a child is not able to master a given task does the teacher switch to step two with the child. In this second step, structure facilitation, the role of the teacher expands while structuring the task, an approach referred to as "teacher-centered instruction." The second step includes direct instruction, an instructional component that increases the impact of the mathematical instruction for students with learning disabilities (Gersten et al., 2009; Kroesbergen & Van Luit, 2003). Within each task on the instructional plan, explicit examples of instruction are clarified for both learning by doing and structure facilitation, which the teacher can use in an individualized manner to meet the instructional needs of each child.

The third feature, the importance of internalization, is based on a theory which states that internalizing mental operation occurs at three discrete levels (Pape & Tchoshanov, 2001). Three levels of material use are therefore offered within the tasks of TRTM: concrete materials, which are tangible objects such as blocks, pawns and fingers; semi-concrete or pictorial representations, such as tallies or dice; and, abstract symbols, which facilitate the transition from concrete quantities, or "material operations," to a mental meaning of number symbols, or "mental acts." The program initially focuses primarily on offering concrete materials (McNeil & Uttal, 2009). Semi-concrete materials are offered later in the program, with the goal of eventually reaching the third level, the internalization of abstract numerical symbols. At the semi concrete level, the more traditional dice-structure and additionally the use of tally-marks, based on the program of Van Luit and Schopman (2000), since the dot structure of the die is not familiar to all children (Papic & Mulligan, 2005), are used as perceptual gestalts – a configuration of elements so unified as a whole that its properties cannot be derived from a simple summation of its parts – the gap between situated knowledge (four concrete objects, such as apples) and formal mathematics (the abstract number symbol 4) can be bridged (Bruner, 1966). The tally-mark use – in which each of the five tallies are enclosed with an ellipse instead of by pulling the first four tallies through with a fifth, long, diagonal tally – helps children understand that the number "5" represents five objects, which corresponds with the natural finger counting strategy of children, and that numbers are based on patterns (5, 10, 15, etc.).

Data analysis

The scores on the five tasks – the ENT-R and the four component tasks of the AWMA – represent the number of correct answers on these tasks. These scores can be considered as valid only if there are no extreme values identified (Tabachnick & Fidell, 2006). For that reason, univariate outliers – scores differing three standard deviations or more from the mean – were removed from the sample. On the dependent variable of early numeracy score at the posttest stage, no univariate outliers were identified. Similarly, no univariate outliers were identified for early numeracy at the pretest stage or for one of the working memory tasks, Word Recall Backward. In contrast, one high score on Dot Matrix (score = 24), one high score on Odd One Out (score = 14) and five high scores (score = 20, 19 or 18) and one low score (score = 5) on Word Recall Forward were removed. This procedure was thus applied to 0.69% of the data points, and only for scores on the independent variables. Other than these eight deleted scores, there were no missing data, except for the four children which moved during the study and were therefore excluded from all further analyses.

Prior to data analysis, it was tested whether a multilevel approach was required for the data (Hox, 2010), because in the design of this study children nested within schools were randomly assigned to condition. In a two-level multilevel model (level 1: individual children; level 2: schools) using HLM7 software (Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2011), the intraclass correlation was calculated to indicate the proportion of variance at school level. The value of this correlation (< 0.001) revealed no random effects on school level on the outcome score. In other words, the early numeracy score at posttest of children in the same school are not more alike than the outcome score of the children in different schools ($\sigma^2_{u0} = 0.03$, $\chi^2(5) = 5.72$, $p = .33$). As a result, no multilevel analyses were carried out.

Data analysis was done in six steps. First, the descriptive statistics of the groups were explored. Then, the main analyses – steps 2, 3, and 4 – were performed using three analyses of variances with covariates (ANCOVAs). In step 2, the three conditions were added as a factor and the pretest early numeracy score was added as a covariate. In step 3 and 4, two similar analyses were performed. In this instance, however, the two target groups within the IG and CG were added as a factor and the pretest early numeracy score was added as a covariate. For all three main analyses, it was also tested whether the results remained similar when controlling for visual and verbal working memory. The partial eta-squared (η^2) is given as a measure of effect size. The critical values for this measure are 0.01 for a small effect, 0.06 for a medium effect, and 0.14 for a large effect (Cohen, 1988). Two additional steps – steps 5 and 6 – were carried out to answer the second research question, which only concerns children in the intervention condition. In the fifth step, the relation between the posttest early numeracy scores and the five predictor variables of visual and verbal working memory, SES, age and gender were explored with correlation analyses. Lastly, stepwise regression analyses were used to investigate which of the predictor variables had contributed to explanations of the variance in children's numeracy skills at the posttest stage.

Results

Table 5.4 provides mean raw scores and standard deviations for early numeracy at both the pretest and posttest stages, and verbal working memory and visual working memory at pretest, parsed by group – TAG, IG, and CG – and by time period – pretest and posttest. Table 5.4 also provides pretest and posttest scores for the two specific target groups in the IG and the CG, students in the 25^{th}–50^{th} percentiles and those below the 25^{th} percentile.

Intervention effects for all children scoring below the 50^{th} percentile on early numeracy

A series of one-way ANCOVAs were conducted to test whether the mean early numeracy gains between the pretest and posttest stages differed between the three groups. Preliminary analyses revealed no group interaction effects involving low SES as compared to high, $F(1,186) = 0.39$, $p = .53$, $\eta^2 = .00$, age, $F(1,186) = 0.00$, $p = .98$, $\eta^2 = .00$, or gender, $F(1,186) = 0.00$, $p = .98$, $\eta^2 = .00$. These factors were therefore excluded as variables in subsequent analyses. The deletions, in turn, served to make the results more parsimonious and easier to interpret.

Although children were randomly assigned to either the intervention (IG) or control group (CG), pretest ENT-R scores were used as a covariate in all four analyses (see Table 5.5) since children from the reference group (TAG) differed significantly from the other two groups in terms of their pretest ENT-R scores. This covariate served the dual purposes of (a) minimizing any potential confounding that might have been attributable to prior numeracy knowledge between the three groups, and (b) reducing unexplained variance and thereby increasing the power of the analyses to detect treatment effects (Field, 2005; Maxwell & Delaney, 2004). A correction for visual working memory was conducted in the second analysis (see Table 5.5), whereas the third analysis was corrected for verbal working memory. In the final analysis, both visual and verbal working memories were included as covariates to compare the effect of both working memory components. Table 5.5 presents the results of the four analyses.

Table 5.4 Early numeracy and working memory scores for three groups and specific target groups (25th–50th and 0th–25th) within the IG and CG

	EN score pretest			EN score posttest			Visual WM pretest			Verbal WM pretest		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
IG	52	12.85	3.48	52	21.02	6.18	50	12.54	3.46	49	12.90	1.97
25th–50th	27	14.93	2.73	27	23.15	5.33	25	12.50	3.80	26	13.07	2.13
0th–25th	25	10.60	2.75	25	18.72	6.30	25	12.58	3.17	23	12.70	1.79
CG	46	12.89	3.52	46	17.89	4.54	45	11.93	3.67	43	12.82	2.12
25th–50th	25	15.16	2.48	25	18.76	4.71	25	12.00	3.77	23	13.25	2.22
0th–25th	21	10.19	2.52	21	16.86	4.21	20	11.85	3.65	20	12.33	1.95
TAG	94	22.34	4.96	94	24.03	6.45	89	13.79	3.38	86	13.96	1.95

Note. EN = early numeracy, WM = working memory, IG = intervention group, CG = control group, TAG = typically achieving group.

Table 5.5 Results of ANCOVAs with condition (TAG, IG and CG) as factor and different covariates

Analysis	Covariates	*F*	*df*	*p*	η^2
1	Condition	13.07	2, 188	.00	.12
	Pretest score EN	124.66	1, 188	.00	.40
2	Condition	14.11	2, 179	.00	.14
	Pretest score EN	108.40	1, 179	.00	.38
	Visual WM	6.06	1, 179	.02	.03
3	Condition	14.36	2, 173	.00	.14
	Pretest score EN	93.09	1 ,173	.00	.35
	Verbal WM	7.29	1, 173	.01	.04
4	Condition	14.55	2, 167	.00	.15
	Pretest score	79.57	1, 167	.00	.32
	Visual WM	4.93	1, 167	.03	.03
	Verbal WM	7.84	1, 167	.01	.05

Note. EN = early numeracy, WM = working memory, IG = intervention group, CG = control group, TAG = typically achieving group.

5

In all analyses a statistically significant and large effect for condition was found on the posttest early numeracy score when corrected for pretest early numeracy score and working memory. Post hoc analyses with a Bonferroni adjustment revealed significantly higher and meaningful adjusted outcome scores for the IG in comparison to the CG (MD = 3.30, $p < .001$), and in comparison to the TAG (MD = 5.78, $p < .001$). The TAG, however, did not differ significantly from the CG (MD = -2.48, $p = .10$). The effect for condition was shown to increase when correcting for working memory, indicating that working memory factored into the effectiveness of the intervention. The growth in effect, however, was minimal when one or two working memory components were added. Based on the final analysis, the effect of verbal working memory looks to be more meaningful in the early numeracy development of young children than visual working memory.

Intervention effects for children scoring between the 25th and 50th percentiles and children scoring below the 25th percentile on early numeracy tests

To test the effectiveness of the intervention for the two specific target groups comprised, respectively, of children scoring between the 25th and 50th percentiles and children scoring below the 25th percentile, two one-way ANCOVAs were conducted to test whether the mean early numeracy gains between the pretest and posttest stages differed between the intervention and control conditions (see Table 5.6). The pretest ENT-R score and visual and verbal working memory again were included as covariates. In none of the analyses was it found that working memory exerted a statistically significant effect, indicating that no differences existed between the mean gains of the IG and CG. For this reason, only the results of the first analyses are presented in Table 5.6. Effect sizes are presented only for those analyses where group differences achieved statistical significance.

Table 5.6 Results of ANCOVAs for specific target groups (25th–50th and 0th–25th) with condition (IG or CG) as factor

Group	Covariates	F	df	p	η^2
25th–50th	Condition	13.52	1, 49	.00	.22
	Pretest score EN	13.65	1, 49	.00	.22
0th–25th	Condition	1.04	1, 43	.31	–
	Pretest score EN	16.22	1, 43	.00	.27

Note. EN = early numeracy, IG = intervention group, CG = control group.

The role of working memory in the measured early numeracy development among children included in the IG

The next step was to explore the relationship between the posttest early numeracy score and six predictive variables relevant to those children included in the IG (Table 5.7). The correlation analyses revealed that the posttest score on the early numeracy test correlated significantly with the pretest early numeracy score (Pearson's p = .62) and with verbal working memory ability (Pearson's p = .34), but not with visual working memory (Pearson's p = .17), age (Pearson's p = .10), sex (Spearman's rho = .62) or SES (Spearman's rho = .62). To determine which of these factors was most important in early numeracy, a stepwise regression analysis was conducted with the pretest early numeracy score and verbal working memory (Table 5.7). The predictive significance of age, sex and visual working memory was checked, but only SES appeared to be of statistical significance. SES was therefore entered as a variable in the second step analyses. Three variables – pretest early numeracy score, SES, and verbal working memory – were entered in this order to examine the added explained variance introduced by verbal working memory.

Analyses revealed an explained variance of 38% for the pretest early numeracy score. In the second step, SES added 7% of the variance. Verbal working memory added an additional 8% of explained variance. In total, 52% of the variance in children's early

Table 5.7 Results of regression analyses for EN posttest score separately for the IG

	B	*SE*	β	*t*	*p*	R^2	ΔR^2	Adj. R^2	*F*	ΔF
Step 1						.38	.38	.36	28.21**	28.21**
Constant	7.51	2.69		2.80	.01					
Pretest score EN	1.07	0.20	.61	5.31	.00					
Step 2						.44	.07	.42	18.07**	5.33*
Constant	8.96	2.65		3.39	.00					
Pretest score EN	1.05	0.19	.60	5.46	.00					
SES	-3.20	1.39	-.26	-2.31	.03					
Step 3						.52	.08	.49	16.08**	7.22*
Constant	-1.07	4.48		-.238	.81					
Pretest score EN	0.92	0.19	.53	4.95	.00					
SES	-4.17	1.35	-.33	-3.09	.00					
Verbal WM	0.94	0.35	.30	2.69	.01					

Note. EN = early numeracy, IG = intervention group, WM = working memory.
** $p < .01$, * $p < .05$.

numeracy scores at the posttest stage could be explained by their pretest score, their verbal working memory ability, and their SES.

Discussion

The primary purpose of this study was to test the effectiveness of a remedial numeracy program for low-performing kindergartners, in order to investigate whether it is possible to stimulate the early numeracy skills of children who experience problems in mastering these abilities. Children scoring below average were the target group for the intervention regimen applied in this study. The IG and CG therefore consisted of children scoring below the 50th percentile. Within these respective groups, a distinction is made between children scoring between the 25th and 50th percentiles and children scoring below the 25th percentile. Those children scoring below the 25th percentile can be labeled as being at risk for developing math-related learning difficulties in their ongoing school career. Intervention at an early stage may give these low-performing children the opportunity to catch up with their typically-achieving peers, thereby allowing them to obtain sufficient basic mathematical knowledge by the start of first grade. This in turn might allow these children to take greater advantage of the education offered during primary school, in terms of both curriculum and instruction.

Main conclusions

Although all three groups made gains in early numeracy over the course of the study, the children included in the IG realized larger gains than those children in the CG and, relatively speaking, than the typically-achieving children. The results revealed a greater improvement in the performance of kindergartners who had scored below average and subsequently attended the TRTM remedial program as compared to children who had scored below average and subsequently participated only in the standard curriculum. Given that kindergarten and first grade early numeracy predicts calculation fluency in second grade (Locuniak & Jordan, 2008) and success rate on a high-stakes state mathematics test in third grade (Jordan et al., 2010), the finding that early numeracy in children who have scored below average can be increased via a relatively brief intervention regimen is encouraging.

Since very low early numeracy in kindergarten can predict the future presence of a math-related learning disability in third grade (Mazzocco & Thompson, 2005), the study also investigated whether this result can be applied to specific target groups of children within the IG and CG. The intervention regimen proved to be effective for children who scored between the 25th and 50th percentile. Differences were found, as well, between the very low-performing children in the IG (<25th percentile) and the very low-performing children in the CG (<25th percentile) at the posttest stage, although these differences did not reach the designated threshold of statistical significance. Based on these results, the conclusion can be drawn that the intervention regimen was effective only for children showing acceptable levels (between the 25th and 50th percentile) of early numeracy at the pretest stage, and was not beneficial for children with very low early numeracy ability (<25th percentile) at the start of the intervention (Fuchs, Fuchs, & Compton, 2012).

The role of working memory in the early numeracy of children attending the intervention sessions was also investigated. Given the unequivocal results presented in prior research about the relationship between working memory and early numeracy performance (e.g., Espy et al., 2004; Kyttälä et al., 2010), it was not surprising that children's verbal working memory skills explained variance observed in early numeracy ability. Participating children better able to temporarily store verbal information, or able to revise such information while simultaneously performing a task, also experienced greater benefits as a result of the intervention. It was unexpected, however, that this relationship with early numeracy scores proved to be evident only for verbal working memory and not for visual working memory. Based on previous research, the efficacy of verbal working memory, as opposed to visual working memory, as a predictor of numeracy development was unclear, because both types of working memory have been repeatedly related to numeracy achievement and development (e.g., Raghubar et al., 2010). The results presented in this study are in line with the meta-analysis presented by Swanson and Jerman (2006), which concluded that verbal working memory ability can characterize children with math difficulties after controlling for the effects of several other variables. Kroesbergen et al. (2007), for example, found that the phonological loop exerted a stronger effect than did the visuospatial sketchpad and early numeracy skills. Other studies, however, have suggested that verbal working memory skills may be more generic in terms of supporting mathematical skills during primary school, while visuospatial working memory may be more specific to early numeracy learning (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003). In the research of Bisanz, Sherman, Rasmussen, and Ho (2005), for example, visuospatial working memory was considered to be the best predictor of early numeracy performance in kindergarten, but not by the time children had entered into the first grade. Although it is not clear precisely how working memory and early numeracy achievement are connected, the studies mentioned above, along with the present study, show the importance of working memory ability in the early numeracy development of young children.

Limitations and future research

A limitation of the present study is the omission of a small group intervention which did not involve numbers or numeracy. It is possible, although not likely, that the early numeracy gains seen in the IG comprised of children demonstrating below average early numeracy were partly the result of special treatment more generally, rather than the specific number-related activities. In future studies, it is recommended that researchers include a general intervention condition, carried out in small groups, to be compared to the number sense condition. In the ideal design, this condition would exist alongside a care-as-usual control condition, as was done in the current study (Ranjith, 2005). This study does, however, illustrate the limitations of offering this sort of intervention regimen over a relatively short period of time. Future studies employing or testing the same or a similar numeracy program should experiment with the length of the intervention period. This will allow researchers to test: first, whether the children scoring below the 25th percentile benefit when the program is offered for a period longer than 8 weeks; second, what program duration produces the best results for children performing below average; and third, whether it is possible for the children achieving a below average early numeracy score – or at least a subgroup of them – to bridge the gap between them and their typically-achieving peers before the end of kindergarten and the start of first grade.

On a practical level, another limitation was the use of trained supervisors in lieu of kindergarten teachers in conducting the intervention sessions. One major goal in developing an intervention program is to explore whether the intervention is effective and applicable within the existing learning environment of the school (Lodico, Spaulding, & Voegtle, 2010). This should be considered in designing future research.

There were also limitations regarding the study design. In future designs, follow-up measurements would allow researchers to examine whether the remedial program led to a deeper understanding of numerical relations and whether the children in the IG realized greater benefits from math education in first grade as a result of the conceptual number knowledge obtained and developed through the intervention regimen.

The present study was conducted using a Dutch, Dutch-speaking sample of kindergartners. This has implications for the wider applicability of results because findings of intercultural studies imply that relational and counting skills are somewhat different (e.g., Aunio, Niemivirta, Hautamäki, Van Luit, Shi, & Zhang, 2006). The Dutch population is to a significant degree characterized by a high number of second generation immigrants from countries around the Mediterranean basin, especially from Morocco and Turkey. In the present study, this is reflected in the connection noted between SES and early numeracy development. It might also be interesting, however, to account for elements such as language (i.e., at-home language and language proficiency) and cultural background when analyzing data on early numeracy, as has been done in previous studies (Aunio et al., 2006; Kleemans et al., 2011).

Implications

The present randomized controlled study demonstrated that key areas of early numeracy in kindergartners scoring below average can be improved upon, but such areas cannot be improved upon for all children with very low early numeracy abilities. Building on prior research (e.g., Baroody et al., 2009; Dyson et al., 2011; Kaufmann et al., 2005; Krajewski et al., 2008; Ramani & Siegler, 2008), the use of numeracy interventions for children with below average scores is advisable, as many such children enter into first grade with far fewer learning experiences than their typical achieving counterparts. Although it seems necessary to offer children with low or very low early numeracy skills remedial instruction, this study could not confirm the efficacy of such regimens for all children.

To summarize, it can be argued that the remedial program led to better performance of early numeracy skills in kindergartners scoring between the 25th and 50th percentile, but not for those children most at risk of developing learning difficulties, with scores falling below the 25th percentile. This study does confirm, however, the assertion that it remains necessary to assist low-performing children at risk of experiencing math learning difficulties through prevention programs with a focus on early numeracy.

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Effects of remedial numeracy instruction throughout kindergarten starting at different ages: Evidence from a large-scale longitudinal study

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Abstract

The aims of this study were to investigate the effects of remedial numeracy support throughout kindergarten and to compare the effects of interventions from different lengths. Support occurred two times per week for 1.5 (90 sessions, complete condition) or 0.5 school years (28 sessions, short condition). Below average students were randomly assigned to complete intervention (N = 155), short intervention (N = 105) or control (education-as-usual, N = 150). Accounting for achievement at pretest, children who received one of the interventions outperformed the control children in early numeracy at post-test and follow-up tests, suggesting that children internalized the knowledge. Transfer effects on simple arithmetic were found for only the complete support group, whereas on complex mathematics both interventions were effective.

Introduction

Early numeracy performance at four or five years of age has far-reaching influence in math learning. Early numeracy skills in kindergarten predict mathematics learning through the end of sixth grade (Kavkler, Aubrey, Tancig, & Magajna, 2000), and even predicts mathematical competence in higher education (Siegler, 2009). Moreover, children who perform lower than peers in basic quantitative knowledge in kindergarten tend to remain behind throughout their schooling (Duncan et al., 2007; Jordan, Glutting, & Ramineni, 2010). Thus, low early numeracy is an indicator of risk for long-term math learning disabilities (Toll, Van der Ven, Kroesbergen, & Van Luit, 2011), and should therefore be supported in the kindergarten years.

In the present study, we investigated the effects of a remedial early numeracy program especially designed for children at risk for mathematical learning difficulties, namely children scoring low on a standardized early numeracy test. The goal was to refine and test two early numeracy program versions of different duration lengths.

Low early numeracy as risk factor

Early numeracy can be defined as the general understanding of numbers (Gersten et al., 2012; Passolunghi & Lanfranchi, 2012), and can be divided into several skills, such as (verbal) counting, knowing the number symbols, recognizing or discerning quantity patterns, comparing numerical magnitudes and estimating quantities (e.g., Gersten, Jordan, & Flojo, 2005). The consequences of (low) early numeracy in preschoolers and kindergartners have been studied repeatedly (e.g. Jordan, Kaplan, Ramineni, & Locuniak, 2009). Most children develop the prerequisites for learning mathematics in a natural way through informal learning in the home environment (e.g. Anders et al., 2011). The fact that this is not true for all young children leads to wide individual differences in early numeracy levels in kindergarten classes (Aunio, Hautamäki, Sajaniemi, & Van Luit, 2009). Whereas most children have mastered a range of early numeracy skills at this point, others do not have a thorough command of numbers, their meaning and their interrelations (Jordan et al., 2010). This causes some children to already trail behind in their early numeracy knowledge by the age of five years and, as a result, make the transition from kindergarten to first grade with an insufficient understanding of numbers and related skills such as counting, estimating and reasoning. Research shows that those children with inadequate early numeracy skills are hardly capable of catching up with their peers, and are thus at risk for developing mathematical learning difficulties at a later stage (e.g., Stock, Desoete, & Roeyers, 2010). Therefore, adequate remedial support should be offered during kindergarten to meet the needs of this at-risk group.

(Remedial) intervention on early numeracy

There is ample evidence that early numeracy can be enhanced through structured intervention (e.g. Griffin, 2004; Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005; Krajewski, Nieding, & Schneider, 2008). Empirical evidence centers around curricular interventions over the long-term, such as Building Blocks (Clements et al., 2011) or Big Math for Little Kids (Greenes, Ginsburg, & Balfanz, 2004). Less information is available about the effects of interventions especially designed for kindergartners at risk of poor mathematics outcomes. Although we identified no randomized control studies contrasting different lengths of intervention, we did locate several randomized control trials assessing intervention efficacy for at-risk students. In most of these studies, children from low-economic status families – classified as being at risk – made significant gains on early numeracy achievement, or accessing those skills, as a target of remedial intervention (Baroody, Eiland, & Thompson, 2009; Dyson, Jordan, & Glutting, 2013; Fuchs et al., 2013; Jordan et al., 2012) or an adaptive game intervention (Wilson, Dehaene, Dubois, & Fayol, 2009). However, in a limited number of studies, children were detected as being at-risk based on their early numeracy abilities (Van de Rijt & Van Luit, 1998; Van Luit & Schopman, 2000). The results of these studies showed that it is possible to stimulate the development of early mathematical competence among young, poor arithmetic achievers, but also that intervention is not always promising for the children belonging to the weakest range or in other words scoring below the

25th percentile (Toll & Van Luit, 2012). As an explanation may lie in the duration of the intervention, in the present study this duration will be manipulated.

The target group of the intervention in the present study are children with a score in the lowest 50 percent range of a Dutch norm group on the Early Numeracy Test – Revised (ENT-R; Van Luit & Van de Rijt, 2009). This criterion is chosen because these children are at low-to-high risk for developing math difficulties. The used intervention program, which is called *The road to mathematics* (Van Luit & Toll, 2012), was especially designed for the support of low-performing children; the program contains an intensive form of over-rehearsal, small task-focused (sub-)goals and clear materials, because these are process variables that provide the foundation for instruction (Fuchs & Fuchs, 2006). There are two versions available of *The road to mathematics*: the complete version can be offered during 1.5 school years; the short version during 0.5 years. Distinction between these two versions is based on previous studies, confirming that the length of an early numeracy intervention matters (e.g. Schopman & Van Luit, 1999). On the one hand, the literature (e.g. Kroesbergen & Van Luit, 2003) shows the value of long-term training, while on the other hand long-term structural support requires increased staffing and additional costs. To meet the needs and the feasibility and costs-benefits criteria from an practical educational point of view, a short version, consisting of a selection of tasks from the complete version, was added as an accelerated alternative to the complete version.

The road to mathematics is a remedial program aimed at accelerating the early numeracy ability of kindergartners scoring below average; it can therefore be used as component of a prevention system within kindergarten aiming to ensure that children start formal math education in first grade with a minimal delay compared to their typically-developing peers (Toll & Van Luit, 2013). Fuchs, Fuchs, and Compton (2012) describe this prevention system as a multitier system where the regular kindergarten curriculum is offered on the first tier. At a second tier, identified weak-performing children receive intensive intervention, often offered in small groups. The purpose of this prevention system is twofold (Fuchs et al., 2012). The first aim is to drastically reduce problems in learning outcomes (and the need for special education), as well as the negative long-term effects which occur when children leave school without the skills they need to function in their subsequent life. The second (complementary) aim of the multilevel system is to identify children with learning disabilities, such as dyscalculia (Butterworth, Varma, & Laurillard, 2011), as non-responders to valid interventions. For this reason, the multitier prevention system is referred to as responsiveness-to-intervention (RTI) (Fuchs et al., 2012).

Present study

The present study aims to demonstrate the effectiveness of two remedial early numeracy interventions with different duration lengths on kindergartners scoring below average. Comparing the two versions addresses the question whether longer-lasting support brings up more positive effects than time-limited remediation started at a later age. The complete version of a remedial program is offered during 1.5 school years and takes place from halfway through the first year of kindergarten until the children transit to first grade, whereas the short version lasts 0.5 school years and starts one year later, halfway through the second year of kindergarten. To understand the efficacy of the two versions, we compared each intervention condition against a control condition of kindergartners scoring below average. To provide information about whether different durations of intervention can help narrow the achievement gap, we included a group of typically-achieving classmates as a second control condition (typically-achieving condition). The two control conditions received the regular curriculum (tasks and instruction as usual), while the intervention conditions followed the intervention lessons. The schools were required to offer the regular curriculum in a systematic manner following a standardized method. In this way, we controlled for the influence of time (all conditions received early numeracy instruction for at least one hour per week) and systematically offering.

In short, the following research questions were addressed:

1. Is the complete version of *The road to mathematics* an effective remedial program for enhancing at-risk kindergartners' early numeracy skills (below the 50^{th} percentile)?
2. Is the short version of *The road to mathematics* an effective remedial program for enhancing at-risk kindergartners' early numeracy skills (below the 50^{th} percentile)?
3. Is the complete version of *The road to mathematics* an effective remedial program for both children scoring below average (between the 25^{th} and 50^{th} percentile) and children with poor achievement scores (below the 25^{th} percentile)?
4. Is the short version of *The road to mathematics* an effective remedial program for both children scoring below average (between the 25^{th} and 50^{th} percentile) and children with poor achievement scores (below the 25^{th} percentile)?

Method

Participants

To increase generalizability, we pursued a sample as representative as possible of the Dutch population. Therefore, we recruited 31 Dutch primary schools in ten (out of twelve) different Dutch provinces to participate in the study. According to facts from the Dutch institute for statistics (CBS, 2011), the distribution of the sample over the four country areas corresponds to the population of Dutch kindergartners (North: Sample (S) = 6.3%, Population (P) = 10.3%; South: S = 17.0%, P = 20.2%; West: S = 31.3%, P = 46.8%; East: S = 45.4%, P = 22.7%). In total, 1,040 children (539 boys, 51.7%) were screened halfway through the first year of kindergarten[1] to identify children scoring below average on a standardized early numeracy test. The mean age of the children at the start of the study was 4.56 years, with a standard deviation of 4.07 months. All of the children's parents gave their consent to the study. Based on the screening outcome at pretest, children were classified into an above average group (scores above the 50th percentile) and a below average group (scores below the 50th percentile). The children in the above average group (N = 630) function as a typically-achieving condition. Within the below average group (N = 410), a distinction is made between children scoring between the 25th and 50th percentile (25-50 condition N = 175) and children with a poor achievement below the 25th percentile (0-25 condition N = 235). Together, the children in the below average group (N = 410) were matched within their own school in groups of three children with a comparable early numeracy screening score. Randomly, one child out of three was assigned to the complete intervention condition (N = 155; 25-50 condition N = 71; 0-25 condition N = 84) and two children to the control condition. After one year, this matching procedure was repeated for only the children in the control condition. These children were randomly assigned to either the short intervention condition (N = 105; 25-50 condition N = 51; 0-25 condition N = 54) or the control condition (N = 150; 25-50 condition N = 53; 0-25 condition N = 97), producing a control condition with the same number of children as the complete intervention condition. This multisite randomized trial design, in which children are randomly assigned within their own school, is chosen to improve the statistical power of the analyses (Raudenbush & Liu, 2000). The number of children with a poor achievement below the 25th percentile were evenly distributed between the three below average conditions (χ^2 (2) = 5.42, p =

1 In the Netherlands, children begin attending kindergarten when they reach the age of four. They attend, on average, two years of kindergarten before moving to first grade in September of the year in which they turn six years old.

.07). Table 6.1 shows the screening data at pretest and information about IQ, age and gender. Compared to the typically-achieving condition (the above average children), the below average children were disproportionately younger (t (1039) = -4.04, p < .01) and had a significantly lower score on an IQ-test (t (682.59) = -9.18, p < .01), but the three below average groups were demographically comparable. The proportion of boys and girls was equal between the below average and the above average group.

During the course of the study, 99 children (9.5%) dropped out because of (a) transition to another school due to moving or transfer to special education (N = 84), or (b) moving up a grade (N = 15). From the remaining cases, 31 children (3.0%) were absent during one of the time points due to illness or technical errors. The distribution of children who left the study is equal between the below average group (46.5%) and the above average group (53.5%). Little's (1988) MCAR test indicated data was missing completely at random (χ^2 (36) = 46.00, p = .12). This means that the missing values pattern was non-informative, i.e. the children who left the study prior to the fifth time point did not introduce significant bias. Due to the application of full information maximum likelihood (FIML) within structural equation modeling, all available scores of the missing children remained included in the analyses (Enders & Bandalos, 2001).

Procedure

We identified kindergartners scoring below average halfway through the first year of kindergarten, and randomly assigned them to the complete intervention condition, the short intervention condition and the regular curriculum control condition (care-as-usual). The remaining above average-scoring classmates function as a typically-achieving condition (regular curriculum) to provide insight into the extent to which different lengths of intervention help narrow the achievement gap. The complete intervention occurred for 1.5 school years (90 sessions, 30 minutes per session, two times per week with at least one day off in between) from halfway through the first year of kindergarten until the end of the second year of kindergarten. The short intervention occurred for 0.5 school years (28 30-minute sessions, two times per week with at least one day off in between). The intervention children did not attend the regular math lessons in the classroom. The schools were required to offer the regular curriculum systematically to the control condition and the typically-achieving condition for at least one hour a week to make it possible to control for the influence of time and systematically offering. The size of the classes in which the curriculum was offered differed from six to 22 children. Both versions of the intervention were offered in small groups (three to five children)

Table 6.1 Descriptive statistics for the four conditions

	Complete			Short			Control			Typically achieving		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
Covariates												
Gender (%)	Boys: 80 (51.6)		Girls: 75 (48.4)	Boys: 59 (56.2)		Girls: 46 (43.8)	Boys: 85 (56.7)		Girls: 65 (43.3)	Boys: 314 (49.8)		Girls: 316 (50.2)
Age (months)	155	53.99	4.26	105	54.22	3.95	150	53.94	4.49	630	55.07	3.90
IQ-score (range: 0–36)	134	24.35	4.71	95	23.78	4.54	120	23.59	5.07	552	26.82	4.31
Early numeracy												
Pretest	155	9.61	4.34	105	9.69	3.96	150	8.94	4.16	630	18.21	6.40
First in-between	153	14.38	5.03	104	13.18	4.04	143	12.63	4.64	622	20.15	6.05
Second in-between	148	27.39	6.61	105	20.18	6.50	133	20.08	6.04	600	30.35	5.79
Posttest	148	28.98	5.24	103	25.42	5.47	131	21.62	6.19	598	30.32	5.44
Follow-up	135	34.07	5.38	97	33.29	6.30	126	30.72	6.98	571	36.41	3.90
Transfer outcome variables												
Simple arithmetic	135	7.44	4.18	97	6.34	3.93	126	5.48	3.76	571	9.13	3.76
Complex mathematics	109	36.39	16.49	71	32.51	16.40	76	24.95	15.60	528	40.18	14.56

Note. Scores for complex mathematics were derived from the school system. For these scores no missing information is available.

by a specialized female teacher from their own school, appointed based on her expertise and kindergarten experience, in a quiet location in the school, outside of the classroom. To avoid contamination, the teachers were not allowed to discuss the content of the program with other teachers within the school. In two schools, the teachers became partly incapacitated during the course of the study due to illness, so a second teacher was added in the execution of the program sessions. The teachers received a training program of five full days in total before and during the intervention period, including background information on early numeracy, role playing, video interaction feedback and exchanging experiences.

To measure the effects of the intervention, early numeracy was measured at five different time points (halfway through – pretest – and at the end – first in-between – of the first year of kindergarten, halfway through – second in-between – and at the end – post-test – of the second year of kindergarten, and halfway through first grade – follow-up test –). To gain insight into the transfer effects of the intervention, we assessed performance on two general math achievement tests (simple arithmetic and complex mathematics) at the follow-up time point halfway through first grade. Also non-verbal intelligence was measured at this last time point. All tests, except for the complex mathematics test, were administered by graduate students in education or psychology (university master's degree), who had trained for the purposes of testing young children. Testers were explicitly not informed about the condition children they were assigned to.

Intervention

Intervention in both conditions occurred following the remedial program *The road to mathematics* (Van Luit & Toll, 2013). There are two versions of the program: a complete version and a short version. The complete version consists of 90 30-minute sessions, the short version of 28 30-minute sessions, both with complete instructional plans and accompanying materials. Each session was divided into two or three separate tasks. Both versions are of a similar structure, consisting of four units of 23 or seven sessions respectively. Each of the four units focuses on a specific number cluster; the numbers up to five, up to ten, up to 15 and up to 20.

The road to mathematics (Van Luit & Toll, 2013) aims to teach low-performing kindergartners a range of basic numerical concepts and math-related language, provide them with the meaning of numbers through structured activities, and therefore simplify the transition to math education in first grade. *The road to mathematics* addresses a wide range of skills, and in doing so offers children a foundation upon which they can build as they enter into first grade.

Implementation fidelity

Implementation fidelity was monitored in three ways: (1) after each session the teacher filled out a digital evaluation checklist including standardized questions about the execution of the sessions and the behavior of the children; (2) once fortnightly, each fourth session was videotaped. From each teacher, 22 video recordings from the complete version and six video recordings from the short version are available. All video recordings were viewed and globally checked on nine implementation criteria (Justice, Mashburn, Hamre, & Pianta, 2008). (3) The implementation was checked by a visit to each school, and by monitoring the process through bimonthly phone calls.

Features

The program is characterized by three main features (the importance of instruction, the importance of language, and the importance of internalization) in order to meet the needs of children experiencing problems in early numeracy skills.

The importance of instruction. All of the program tasks were presented to the children through two different instruction steps for each task (e.g. Norris & Ortega, 2001): learning-by-doing and structure facilitation. In the first step, children are exposed to learning-by-doing, also referred to as "learner-centered instruction." The teacher has a guiding and stimulating role, and asks open-ended questions. Only when a child is not able to master a given task does the teacher switch to step two: structure facilitation. The role of the teacher expands while structuring the task, an approach referred to as "teacher-centered instruction." This includes direct instruction – an instructional component that increases the impact of the mathematical instruction for students with learning disabilities (Gersten et al., 2009; Kroesbergen & Van Luit, 2003). Within each task, explicit examples of instruction are clarified for both learning-by-doing and structure facilitation, which the teacher can use in an individualized manner to meet the instructional needs of each child.

The importance of language. Within *The road to mathematics*, a distinction is made between "math language" – words that are directly necessary to perform math problems and calculations (such as "one," "more," "less" or "higher") – and "instruction language" – language that is necessary to complete the appropriate numeracy task in an acceptable manner or to explain an adequate solution ("strategy") for a problem (such as "in-a-row" or "one-by-one"). The relevant math and instruction language for each task was highlighted in a separate frame, so that the teacher could use the specific to-be-learned terms extensively in an effort to elicit the same language from the children. The teacher provides the math and instruction language explicitly during each task, because research has shown a significant relation between the amount of teachers' math-related talk and the growth of preschoolers' conventional mathematical knowledge over the school years (Klibanoff et al., 2006).

The importance of internalization. This feature is based on a theory which states that internalizing mental operation occurs at three discrete levels (Pape & Tchoshanov, 2001). Three levels of material use are therefore offered as part of *The road to mathematics*: concrete materials, which are tangible objects such as blocks, pawns or fingers; semi-concrete or pictorial representations, such as tallies or the dice structure; and abstract symbols (Elia, Gagatsis, & Demetriou, 2007), which facilitate the transition from concrete quantities, or "material operations," to a mental meaning of number symbols or "mental acts." The program initially focuses on offering concrete materials (McNeil & Uttal, 2009). Semi-concrete materials are offered later in the program, with the goal of eventually reaching the third level – the internalization of abstract numerical symbols. The use of tally marks, based on the program of Van Luit and Schopman (2000), as well as the more traditional dice-structure, are representations which function at the semi-concrete level. The structures symbolize the reality, but are more abstract than reality, and therefore function as a semi-concrete in-between stage which attempts to bridge the gap between present knowledge of quantity and formal symbol use (Bruner, 1966). Using these structures as perceptual gestalt – a configuration of elements so unified as a whole that its properties cannot be derived from a simple summation of its parts – the gap between situated knowledge (four concrete objects such as apples) and formal mathematics (the abstract number symbol "4") can be bridged. The tally-mark use – in which each of the five tallies are enclosed with an ellipse instead of by pulling the first four tallies through with a fifth, long, diagonal tally – helps children understand that the number five represents five objects and that numbers are based on patterns (five, ten, 15, etc.). The number five was chosen in part because patterns of five suit the decimal system, and correspond with the natural finger-counting strategy of children. This structure will, moreover, stimulate shortened counting when a child discovers that an ellipse always includes five tallies. Shortened counting means that a child recognizes one ellipse and two tallies as five and two, so that he or she can count from five up to seven (five, six, seven) instead of starting to count from the first tally. The tally-mark method is added next to the more traditional dice-structure, as some children found the dice-structure ambiguous and unstructured (Van Luit & Schopman, 2000).

Domains

Evidence from experimental and educational studies of typically-developing children supports the idea that mathematical ability is not unitary, but is made up with different components (Dowker, 1998; Ginsburg, 1977) and so many skills that are included and necessary in preparatory math education. Based on empirical study results, *The road to mathematics* covers and integrates a wide range of skills to offer children a complete basis which they can build on in first grade. Within *The road to mathematics*, a division is made between ten different domains. Each domain, in turn, is operationalized into several subskills. Detailed information about these domains is presented in Table 6.2.

Within the program, special attention is paid to the linkage ("the mapping") of the domains of verbal counting, concrete counting, semi-concrete structures and abstract number symbols (domains four to seven). These domains represent four different number aspects. In order to understand a given number completely, a child must master all four aspects and, furthermore, a child should understand how these four aspects can be interlinked. A child should learn to link the number word "six" (verbal aspect) to six concrete blocks (concrete aspects) to a dice with six dots (semi-concrete aspect) and to the Arabic number symbol "6". Besides learning the four aspects, a lot of effort in the program is made to teach the children the relation between the four number aspects. Therefore, specific tasks are included that support, for example, the knowledge that a specific number symbol represents a specific amount of concrete objects.

Instruments

Within the measures, a distinction was made between three math measures (i.e. outcome measures) and one cognitive measure (i.e. covariate).

Math measure: Early numeracy

Early numeracy was measured with the Early Numeracy Test-Revised (ENT-R; Van Luit & Van de Rijt, 2009). The ENT-R is a 45-item standardized pencil-and-paper test for children between the ages of four and seven years. The test consists of nine parts that are indicators of early numeracy. The components can be divided into nine components (concepts of comparison, classification, correspondence, seriation, using numerals,

Table 6.2 Ten domains of *The road to mathematics*, operationalized into sub skills and described in activities

Domain	Sub skills	Activities
1. Math language	Position words	The children represent a rhyme about little mousses and a chair: under, next to, up, behind, etcetera; children are standing in a row (or 'a train') and had to name their position compared to the others; children had to carry out several commands including position words (all boys go under the table, etc.).
	Ordinals	Children are standing in a row (or 'a train') and practicing ordinals: the first child is the machinist, the third child goes out of the train, etc.
2. Reasoning skills	Correspondence	A rhyme of ten blue flies is read and each time a blue fly disappears in the thyme, the children have to turn around one of the cards with a blue fly on it; matching a certain number of pawns to an equal number of blocks.
	Comparison	The length of the children or concrete objects of different sizes (in rows or staples) are used to explain the concept of comparison.
	Classification	The shoes of the children have to be classified in several ways; by size, color, number of holes, etc; likewise with colored cards with animals in different amounts on it.
	Seriation	The length of the children or concrete objects of different sizes (in rows or piles) are used to explain the concept of seriation.
3. Measuring & Geometry	Length and content	The children learn to compare different lengths (both qualitative and quantitative) with concrete objects of different sizes (in rows or piles), the height of places or distances between objects.
	Shapes and figures	Finding, naming, coloring shapes and figures.
	Construction	The children learn (re-)building different types of construction in order to learn characteristics of for example block towers.
	Orientation	The children are asked to estimate the distance to an object, then count their steps and decide to what extent their estimation was correct.
4. Verbal counting	Acoustic – forwards	The children practice their counting skills forwards with songs, rhymes, together with small and large movements, counting together or counting alone.
	Acoustic – backwards	The children practice their counting skills backwards with songs, rhymes, together with small and large movements, counting together or counting alone.
	Skip counting	Counting in twos, for example by one child saying the even numbers and the other child saying the odd numbers.
5. Concrete counting	Synchronic	Synchronic counting is practiced by counting concrete objects; by adding one pawn for each counting word; by walking the number tiles path and say the number their standing on.
	Resultative	While counting concrete objects the children have to determine the quantity of the final set.
	Skip counting	Counting in twos by objects in two different colors or by walking over the number tiles path in steps of two.
	Shortened – counting on	The tally mark method, the finger structure and concrete objects are used to teach the children to count on from five.

Table 6.2 continues on next page

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Table 6.2 *Continued*

Domain	Sub skills	Activities
6. Semi-concrete structures	Tally marks – tallies	(Flash) cards and dices with the tally marks on it are used to practice the structure and for games like bingo and linear board games.
	Tally marks – picto	(Flash) cards and dices with the tally marks on it are used to practice the structure and for games like bingo and linear board games.
	Dice – dots	(Flash) cards and dices with the dice structure on it are used to practice the structure and for games like bingo and linear board games; children have to collect cards of all possible amounts (1 to 5) in a memory game.
	Dice – picto	(Flash) cards and dices with the dice structure on it are used to practice the structure and for games like bingo and linear board games; children have to collect cards of all possible amounts (1 to 5) in a memory game.
7. Abstract numbers	Number symbols	Children search for symbols in the classroom; children play bingo games, children walk over a number path of tiles, number cards are matched to the corresponding object sets or dice structure.
8. Number lines	Position	A linear number board game and a linear number bingo game are used to practice with horizontal number lines. A number tiles path is used to practice with vertical number lines. For example, the children walk or jump over the tiles (in one or twos) or had to figure out which number is turned upside down.
	Difference	When walking the number tiles path or playing the linear number board game, the children learn the difference between numbers by following instructions. How many steps do you make to walk from 2 to 4?
	Relation	Children have to decide which numbers are 'neighbors' of the number lying on the ground in the number tiles path.
	Estimation	On the number tiles path, the children have to estimate were a tile must lie between 1 and 10 or 1 and 20.
9. Simple calculation	Combinations	By manipulating concrete objects children learn how the numbers up to 5 can be divided into different combinations (for example 4 = 2 and 2, 1 and 3, and 3 and 1).
	Equal sharing	By manipulating concrete objects children learn how the numbers up to 10 can be divided into equal quantities.
	Addition	Manipulating concrete objects with a short story or rhyme; or by a rover that adds a number of concrete objects while the children close their eyes. Not the calculation itself is the goal, but a better understanding of the numbers in relation to each other is the main goal.
	Subtraction	Manipulating concrete objects with a short story or rhyme; or by a rover that takes away or set a number of concrete objects while the children close their eyes. Not the calculation itself is the goal, but a better understanding of the numbers in relation to each other is the main goal.
10. Working memory	Visual working memory	Playing the classical memory task (with only cards or with both cards and a dice); classifying cards by two colors, while children have to remember the numbers that were classified in each group.
	Verbal working memory	In turn children have to repeat a sequence of words and add a new word to the sequence ("I'm going on holidays and I bring.. or I walk in the zoo and I see.."); children had to remember the quantity they diced before moving their pawn in the linear number board game.

synchronized and shortened counting, resultative counting, general understanding of numbers, and estimation). Each component contains five consecutive items. The total of correct answers (0–45) is the final score. There are two versions of the test, version A and version B. Version A was administered at time points 1, 3 and 5, version B at time points 2 and 4. The reliability coefficient of both versions of the test was good (for both versions $\alpha = .94$; Van Luit & Van de Rijt, 2009). For each time point in the current data a principal component analysis (PCA) with varimax rotation on the nine components was conducted, all revealing one factor explaining between 37.47 and 45.20 of the variance (Table 6.3). Prior to the five PCA, the Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) measure were used to test whether factor analysis is appropriate for these data. The Bartlett's Test of Sphericity was significant for all five time points (Table 6.3), which means that there are some relationships between the variables, and all four KMO measures fall into the large range (Hutcheson & Sofroniou, 1999). On the basis of both statistics it can be concluded that factor analyses are appropriate for the five time points. Reliability analyses revealed good internal consistency of the factor for the four time points varying from .76 at follow-up to .84 at pretest (Table 6.3).

Math measure: Simple arithmetic

Simple arithmetic skills were tested using the first column of the Speeded Number Facts Test (De Vos, 1992). This is a numerical facility test which requires children to solve as many addition fact problems (e.g. 2+4=_) as possible within one minute. The available norms has been standardized on a sample of 10,059 children (Ghesquière & Ruijssenaars, 1994). The cronbach's alpha computed in previous studies was $\alpha = .90$ (e.g., Stock et al., 2010).

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Table 6.3 Statistics of principal component analyses, Bartlett's tests of sphericity, the Kaiser-Meyer-Olkin (KMO) and reliability analyses for the early numeracy test-revised on each time point

	Pretest	1st in-between	2nd in-between	Posttest	Follow-up
R^2	45.20	40.52	42.08	38.79	37.47
Bartlett's χ^2	2664.05	2106.63	2217.47	1818.43	1646.27
df	36	36	36	36	36
p	.00	.00	.00	.00	.00
KMO	.92	.90	.91	.89	.89
α	.84	.81	.82	.80	.76

Math measure: Complex mathematics

Complex mathematical ability was administered with the standardized math test of Cito (Janssen, Scheltens, & Kraemer, 2005). This "Cito"-test is a national Dutch test with good psychometric properties that are commonly used in Dutch schools to monitor the progress of primary school children. For each grade, there are two level-appropriate tests: one is administered in January, the other in June (the halfway point and end of the school year). In first grade, five main domains are covered: (1) numbers and number relations, covering the structure of the number line and relations between numbers; (2) simple addition and subtraction; (3) simple multiplication and division; (4) complex math applications, often involving multiple mathematical manipulations; and (5) measuring (e.g. weight and length). However, this division is not clear-cut: many problems tap knowledge from more than one domain, and the number and relative difficulty of problems per domain varies per wave, because each test reflects the skills that have been learned in that specific period. Therefore, it is not possible to investigate subdomains of mathematics; instead, only the final score can be used as an indication of broad complex mathematical skills. The problems are presented in a booklet. Each problem comes with a picture that sometimes, but not always, contains necessary information. The test is administered group-wise by the teacher, who reads the problems out loud. The test contains 50 items that are administered on two separate days. Raw scores are converted into competence scores that increase throughout primary school, enabling the comparison of results of different tests. Reliability of the first grade test has been computed on $\alpha = .92$ (Janssen et al., 2005).

Cognitive measure: Non-verbal intelligence

The Raven's Colored Progressive Matrices (Raven, 1962) was used to assess the level of general non-verbal intelligence. In this task the child had to solve 36 puzzles with increasing difficulty. In each puzzle a visual pattern was presented, including a missing piece. The child had to choose out of six alternatives the correct piece that was missing in the puzzle. The score represents the number of correct answers on the 36 puzzles. Cronbach's alpha was .90, indicating good reliability (Raven, 1962).

Data analyses

To answer all four research questions, four different models are designed within a structural equation modeling (SEM) framework using the Mplus statistical package

(Version 6; Muthén & Muthén, 1998–2010). As is common in SEM, model fit was evaluated with reference to the root mean square error of approximation (*RMSEA*) and comparative fit index (*CFI*) using the criteria suggested by Blunch (2008): *RMSEA* is good if value is < .05 and acceptable if value is < .08; *CFI* is good if *CFI* is > .95 and acceptable if *CFI* is > .90. In SEM, standardized estimates correspond to measures of effect size. Cohen (1988) defines standardized coefficients around .10 as a small effect, around .30 as a medium effect and greater than .50 as a large effect.

Besides the benefit of including all variables into one single model, the reasons SEM-analyses are applied in favor of more classical analyses are twofold. First, SEM enables the model to take the nested structure of the data, with children nested in schools, into account. Although the number of children in some schools was rather low, ignoring this multilevel structure might have led to unreliable standard errors of the coefficients of the model (Hox, 2010). Intraclass correlations (ICCs) are used as a measure for variance in achievement outcome existing between schools. To test whether the variance is large enough to correct for, the design effect (DEFF) is calculated using a formula specified by Walker and Young (2003). In this formula, the ICC and the average cluster size are used to calculate the DEFF. The estimated standard errors should be adjusted for the multilevel structure of the data when DEFF is larger than two. Since missing data is a potential problem in all large-scale longitudinal studies, the second reason for SEM analyses is that SEM knows how to cope with missing data. In the present study, 10.7% of the scores were missing at the last time point. Due to the full information maximum likelihood (FIML) approach implemented in Mplus, all available scores of the missing children remained included in the analyses (Enders & Bandalos, 2001).

The research questions were examined by fitting four multivariate regression models. In all four models, four outcome variables were included as dependent variables. Two dependent variables (early numeracy achievement at post-test and at follow-up) are used to test direct effects, and two (performance on simple arithmetic and complex mathematics at follow-up) are used to test transfer effect. Four child factors (pretest early numeracy level, non-verbal intelligence, age and gender) were entered as covariates. The covariates serve the dual purposes of minimizing any potential confounding that might be attributable to prior numeracy knowledge between the four conditions, reducing unexplained variance and thereby increasing the power of the analyses to detect treatment effects (Field, 2009).

In the first model, focusing on the effectiveness of the complete intervention (research question 1), three dummies (complete intervention condition as the reference group) were entered as independent variables. The second model was a replication of the first model, but now with the short intervention condition functioning as a reference group (research question 2).

The third model was based on the first model, while the fourth model was based on the second model. In these two new models a grouping command was added to test differences between the poor achievement children (below the 25th percentile) and the children scoring between the 25th and 50th percentile (research question 3 and 4). To make this comparison possible, the third dummy (contrasting the selected intervention condition with the typical achieving children) was left out of the new models.

Results

Descriptive statistics

Table 6.1 shows descriptive statistics for the covariates and the outcome measures separately for the four conditions. From pretest to post-test, the control children went from 19.9% to 48.0% correct, whereas the intervention children went from 21.4% to 64.4% correct (complete version) and from 21.5% to 56.5% correct (short version), and the typically-achieving condition went from 40.5% to 67.4% correct.

Bivariate correlations among all variables were also examined before the multivariate analyses were conducted. To aid visibility and reduce the size of the results section, the correlation matrix is not presented. All correlations were low to moderate. There was no indication of multicollinearity problems in the subsequent analyses.

Effectiveness of the complete intervention (research question 1)

First, an intercept-only model was used to calculate the intraclass correlations (ICCs) and the design effect (DEFF) for the four outcome variables. The ICCs were .20 (post-test early numeracy), .22 (follow-up early numeracy), .11 (simple arithmetic), and .27 (complex mathematics). Together with an average cluster size of 30.75, this leads to a DEFF larger than 2. Thus, the multilevel structure is maintained in the subsequent model. In order to answer research question 1, the model (Figure 6.1) was first tested with the complete intervention condition as reference group (Table 6.4). In the model, outcome scores are corrected for early numeracy achievement at pretest, age, gender and non-verbal intelligence score.

A distinction is made between direct effects and transfer effects. Early numeracy achievements at post-test and at follow-up are used to test direct effects, while

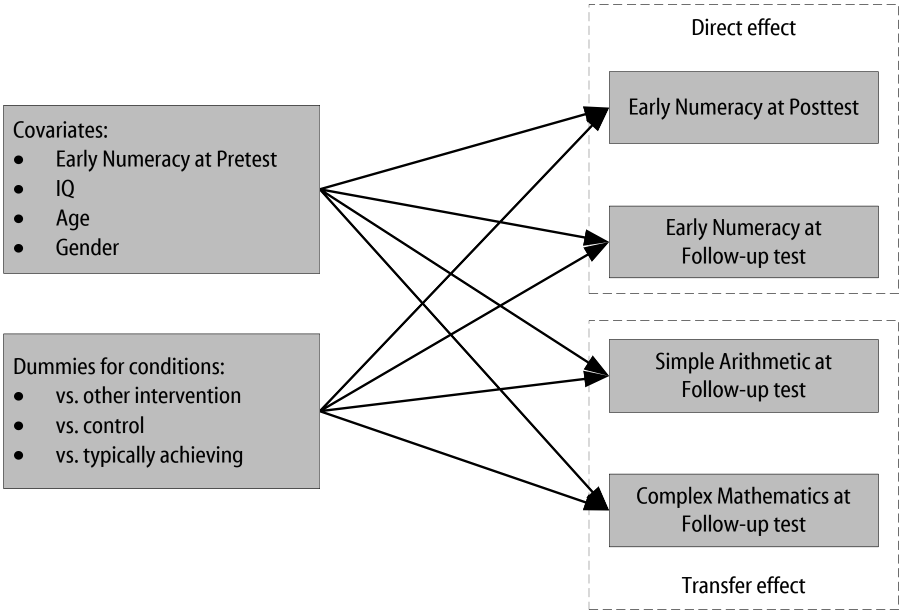

Figure 6.1 Multivariate regression model within a structural equation modeling framework.

performance on simple arithmetic and complex mathematics at the follow-up time point are used to test transfer effect. At post-test, the children in the complete intervention significantly outperformed the children in all other three conditions. Of the nine comparisons on follow-up scores, five were statistically significant in favor of the complete intervention condition. On all three tests at follow-up, the children in the complete intervention condition outperformed the children in the control condition. Compared to the short intervention condition, a transfer effect was found on simple arithmetic, whereas compared to the typically-achieving condition, a transfer effect was revealed on complex mathematics.

Effectiveness of the short intervention (research question 2)

The same model (Figure 6.1) was tested with the short intervention condition as reference group (model 2). The model fit was good (*RMSEA*: 0.03; *CFI* = 0.99). Except from some slight differences in the parameters, the coefficients for the covariates, the explained variance and the intraclass correlations were identical (see Table 6.4). Compared to the control condition, direct effects (early numeracy achievement) for the short intervention were found at both post-test (B = -0.22; SE = 0.05; p < .01) and follow-

Table 6.4 Standardized estimates of multilevel linear regression model predicting the four outcome variables (complete intervention is reference group)

Predictors	Model 1: complete intervention							
	Intervention effects				Transfer effects			
	Posttest EN		Follow-up EN		Follow-up simple arithmetic		Follow-up complex mathematics	
	B	*SE*(B)	B	*SE*(B)	B	*SE*(B)	B	*SE*(B)
Covariates at child level								
Pretest EN	0.38**	0.04	0.30**	0.04	0.40**	0.04	0.43**	0.06
IQ	0.29**	0.03	0.29**	0.05	0.20**	0.03	0.29**	0.04
Age	0.06*	0.03	0.05	0.05	0.15**	0.04	-0.04	0.06
Gender	-0.03	0.03	0.05*	0.03	-0.03	0.03	-0.06*	0.03
Dummies for conditions (ref: complete intervention)								
vs. short intervention	-0.16**	0.03	-0.04	0.03	-0.08#	0.04	-0.07	0.04
vs. control	-0.40**	0.05	-0.20**	0.04	-0.13**	0.04	-0.21**	0.04
vs. typically achieving	-0.24**	0.04	0.06	0.04	-0.08	0.05	-0.13**	0.04
R^2	.48**	.03	.33**	.03	.36**	.03	.41**	.07
ICC	.11		.09		.09		.14	
Model fit indices								
RMSEA	0.03							
CFI	0.99							

Note. EN = early numeracy, ** $p < .01$, * $p < .05$, # $p < .10$.

up (B = -0.16; SE = 0.03; p < .01). Focusing on the transfer effects, the children from the short intervention condition outperformed the children in the control condition in complex mathematics (B = -0.13; SE = 0.07; p = .03), but not on simple arithmetic (B = -0.05; SE = 0.04; p = .23). No effects were found when comparing the short intervention condition with the typically-achieving condition.

Comparing below average children with poor achievement children (research question 3 and 4)

Two additional models (model 3 and 4) were used to test whether the effectiveness is similar for the poor achievement children (below the 25th percentile) and the children scoring between the 25th and 50th percentile. Table 6.5 shows a few differences compared to the overall effectiveness scores from Table 6.4. When it comes to the poor achievement children, the complete intervention condition performs slightly better than the short

Table 6.5 Standardized estimatesof multilevel linear regression model with a grouping command predicting the four outcome variables

Dummies	Intervention effects				Transfer effects			
	Posttest EN		Follow-up EN		Follow-up simple arithmetic		Follow-up complex mathematics	
	B	*SE*(B)	B	*SE*(B)	B	*SE*(B)	B	*SE*(B)
Model 3: poor achievement group								
complete vs. short	-0.25**	0.04	-0.10#	0.05	-.016*	0.07	-0.01	0.10
complete vs. control	-0.50**	0.06	-0.26**	0.04	-0.19*	0.08	-0.32**	0.05
Model 3: between 25th and 50th group								
complete vs. short	-0.23**	0.05	0.04	0.06	-0.09	0.11	-0.16*	0.08
complete vs. control	-0.60**	0.08	-0.21**	0.08	-0.18*	0.08	-0.27**	0.10
Model 4: poor achievement group								
short vs. control	-0.23**	0.09	-0.15*	0.06	-0.02	0.07	-0.31**	0.12
Model 4: between 25th and 50th group								
short vs. control	-0.37**	0.08	-0.25**	0.08	-0.09	0.10	-0.12	0.10

Note. EN = early numeracy, ** $p < .01$, * $p < .05$, # $p < .10$.

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intervention on follow-up early numeracy and simple arithmetic, whereas the children scoring between the 25th and 50th percentile do not outperform the short intervention condition on these test scores. While the poor achievement in the short intervention condition outperform their matched control children on complex mathematics, this effect does not reach significance for the children scoring between the 25th and 50th percentile.

Conclusion and discussion

Early numeracy is a core predictor of later mathematical achievement and development, representing a critical intervention target for low-performing kindergartners at risk of developing mathematical learning problems. In the present study, we investigated the effects of remedial early numeracy support of two different duration lengths on children scoring below average on a standardized early numeracy test (research question 1 and 2). We distinguished four different conditions. The two intervention conditions were offered the remedial early numeracy program *The road to mathematics*. Besides direct effects on an early numeracy test, we also assessed transfer effects on simple arithmetic skills and complex mathematical computations at the first grade level. In addition we tested whether the effects were similar for children scoring between the 25th and 50th percentile and poor achieving children scoring below the 25th percentile (research question 3 and 4).

Although all children made gains in early numeracy during the intervention period, the intervention conditions clearly outperformed the control children at post-test and at follow-up test (when controlling for early numeracy pretest performance, non-verbal intelligence score, age and gender). The strong effects at the follow-up test for both intervention conditions suggest that children internalized what they had learned. So the results revealed a higher performance improvement of low-performing kindergartners that attended the remedial program compared to children participating in the regular curriculum instead. Application of the early numeracy program did indeed influence the development of early numeracy of the participating children in the two intervention conditions. Based on this result, the conclusion can be drawn that through structural support, children can be made aware of the meaning of numbers, their interrelations, and related skills such as measuring and geometry. This implies that by using *The road to mathematics* it is possible and necessary to offer children with low early numeracy skills remedial instruction. This type of remedial support holds promise for evidence-based response-to-intervention service delivery models in school (Barth et al., 2008; Fuchs et al., 2007; Fuchs et al., 2012).

When taking the early numeracy achievement at pretest into account, the children who received the 1.5 school years intervention performed better at post-test, but no longer at follow-up, than the children who received the short intervention during 0.5 school years. This indicates that, in the short-term, structural support over a longer period is more effective. However, effects of long-lasting support do not remain better than effects of an intervention within a shorter time frame. In the present study, the post-test took place at the end of kindergarten, while the follow-up test was administered halfway through first grade. This means that in this in-between period, the children made the transition to formal mathematics education. It could be the case that the intervention effects became similar for both intervention conditions, because children from both interventions had such a basic knowledge and practiced skills that they could optimally benefit from the offered math instruction in first grade. Future research is necessary to investigate this suggestion about the timing of the moment of testing after intervention.

We were not surprised that children in the two intervention conditions made more gains than the children in the control condition in early numeracy, since these skills were targeted during the activities in *The road to mathematics*. It is noteworthy, however, that many of the intervention children were able to transfer this knowledge into more complex abilities which were not presented in the activities of the program. This can be concluded based on an investigation between transfer effects to simple arithmetic skills and complex mathematical computations halfway through first grade (follow-up test). In terms of simple arithmetic skills, the complete intervention children outperformed the control children after receiving about four months of formal math instruction. When comparing to the control condition, no transfer effects were found for the short intervention. On top of that, the short intervention children turned out to be less skilled in executing simple addition problems than the complete intervention children. One possible explanation for this issue is that practicing early numeracy over a longer time period provides the children more memorized knowledge on numbers, which is demanded in the simple arithmetic test rather than the complex mathematic task. As in terms of complex mathematical computation, transfer effects existed for both intervention conditions. Children receiving structural remedial support during kindergarten turn out to be better in mathematical proficiency than their classmates attending the regular curriculum. This finding suggests that children transferred the knowledge they gained during the intervention to less familiar, more conventional skills.

It was also examined whether intervention can help narrow the achievement gap by including a condition consisting of typically-achieving classmates. Even though the typically-achieving children gain the highest early numeracy scores on both post-test and follow-up, when initial early numeracy achievement was held constant, the children in the complete intervention condition showed more improvement at post-test than the typically-achieving condition. This was not the case for the short intervention condition. Moreover, on complex mathematics, the children that received 1.5 school years of support score relatively better than their typically-achieving peers. Again, this was not the case for the short intervention condition. The scores of the children in the complete intervention condition came close, but were not fully similar, to the scores of the typically-achieving children, which implies that it may be possible for the at-risk children to catch up with their typically-achieving peers before they start formal math education at six years old in first grade.

To gain better insight for whom the intervention is effective a distinction was made between poor achievement children, scoring below the 25th percentile, and children scoring between the 25th and 50th percentile. Although the effectiveness results were not very ambiguous, it can be concluded that positive results were found for both subgroups. However, the effect sizes were slightly stronger for the poor achievement children, especially when they followed the complete version of the program, which can probably be ascribed to the lower starting level of these children providing them more developmental opportunities. In a previous study those poor achievement children did not benefit from a shortened version of this remedial program (Toll & Van Luit, 2012), emphasizing the importance of structural long-lasting remedial education for poor achievement children being mostly at risk.

Overall, it can be concluded that more progress was achieved by needs of the complete version of *The road to mathematics*. This confirms the value of long-term training, which has previously been supported by the literature (e.g. Kroesbergen & Van Luit, 2003). Yet, also the short intervention, consisting of a selection of tasks from the complete version, provided a beneficial contribution to the early numeracy development of at-risk kindergarten. Therefore, taking requirements such as increased staffing and additional costs into account, the accelerated alternative seems to be a suitable alternative for the intensive complete version.

The effects of the early numeracy intervention, as was demonstrated in the present study, is congruent with a large number of studies examining intervention effects (e.g., Baroody et al., 2009; Jordan et al., 2012). However, to our knowledge this is the first study that shows the possibility to support early numeracy skills in a more intensive ongoing assistance format, with the aim of preparing children for success in primary school mathematics.

The current study controlled for the first time the different conditions of received math instruction and also for the influence of systematic offering. As a consequence, the children in the intervention condition did not attend the mathematical lessons in a classroom setting. Because it has been found that supplemental interventions are more effective when they are aligned with what takes place in the classroom (Fuchs et al., 2008), in future this design should be adapted. Another limitation of the study is the lack of a small group intervention comparison group – one that did not involve numbers. It is possible, although not likely, that the early numeracy gains were the results of special treatment more generally rather than the specific trained activities. Within the present study, however, it was examined whether remedial education is an effective way to support early numeracy development, and it turned out to be so. Yet, it is possible that the early numeracy gains in the intervention groups were (also) the result of special treatment or small group instruction more generally, rather than the content of the remedial program. Nevertheless, in this study, four different conditions were included to provide optimal information about the intervention effects. Furthermore, it should be noted that we controlled for the variance between schools in the present study. Our results should motivate future research in general education classrooms to investigate methods for enhancing development in early numeracy, and to assess differently from the remedial instruction offered in the present study.

Overall, findings from the present study demonstrates that early numeracy intervention over a period of 1.5 school years is effective for enhancing arithmetic, complex mathematics and early numeracy skills in children with established risk of mathematical learning difficulties. Intervention over a shorter time frame also led to a better performance of early numeracy skills, but showed less strong effects. This study confirms the statement that it remains necessary to assist children at risk of math learning difficulties with remedial support throughout kindergarten.

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The development of early numeracy ability in kindergartners with limited working memory skills

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Abstract

Research has proven limited working memory skills to be a high risk factor for educational underachievement in mathematics across the primary school years. Less is known, however, about the performance of children with limited working memory skills in early numeracy tasks. The main purpose of the two studies reported in this article is to explore the difficulties these children experience in performing early numeracy tasks. In both studies, children with very low working memory skills were identified from a large sample (N = 939), in order to examine in which early numeracy domains they lag behind (Study 1,2) or develop more slowly (Study 1) than their typically developing peers. Results show weaknesses in almost all domains of early numeracy (Study 1) but, against expectations, no pattern in early numeracy could be seen that distinguishes children with problems in verbal working memory from children with problems in visual working memory (Study 2).

Introduction

The term working memory refers to the ability to store and manipulate information simultaneously (e.g. Baddeley, 1986; Baddeley & Hitch, 1974; Just & Carpenter, 1992). In other words, it is the ability to store information temporarily and revise it in the light of new incoming information. The basic modular structure of working memory has proven to be stable and assessable by the age of four (e.g. Alloway, Gathercole, Kirkwood, & Elliott, 2008; Alloway, Gathercole, Willis, & Adams, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004a). Alloway, Gathercole, and Pickering (2006) explored the structure of verbal and visuospatial short-term and working memory in young children and created a model in which a distinction is made between a storage and an updating component, and between verbal and visual working memory. This two-factor model constituted the foundation for the measurement of memory in the two studies reported in this article.

Research has shown large variation in the capacity of working memory in young children and close links between this capacity and learning abilities during childhood (Courage & Cowan, 2009). There is evidence for close links between children's performance in national curriculum assessments at seven years of age and their working memory skills (Gathercole, Pickering, Knight, & Stegmann, 2004b). It appears that limited working memory skills constitute a high risk factor for educational underachievement for schoolchildren across the primary school years (Alloway, Gathercole, Kirkwood, & Elliott, 2009), and furthermore for problems in the attention area (Gathercole et al., 2008). Children who fail to achieve expected levels of attainment for their age in one or more areas of curriculum assessment perform poorly in tests of working memory function (Gathercole & Pickering, 2001; Gathercole et al., 2004b; Mäehler & Schuchardt, 2009), and children with dyscalculia show deficits in specific working memory components (Schuchardt, Mäehler, & Hasselhorn, 2008). This implies that working memory ability, as a supplement to more domain-specific tasks, might be a good predictive measure for identifying children at risk of developing learning difficulties at an early stage, and therefore could be helpful in screening and signaling children at risk of learning difficulties. Of course, there are other risk factors, especially intelligence, to take into consideration in terms of the relation between working memory and specific learning skills. Because, however, of the strong relation that is found between (weak) intelligence and (limited) working memory skills (e.g. Colom, Flores-Mendoza, & Rebollo, 2003; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; De Smedt et al., 2009; Krajewski & Schneider, 2009a; Oberauer, Schulze, Wilhelm, & Süß, 2005; Schuchardt, Gebhardt, & Mäehler, 2010), the studies reported here will focus solely on working memory ability.

One of the educational cognitive abilities that are believed to be underpinned by working memory ability is the learning of mathematical skills (e.g., Vukovic & Siegel, 2006). Working memory is considered important for mathematical performance because incoming information must be stored and manipulated during mathematical problem-solving. The review by Raghubar, Barnes, and Hecht (2010) supports the notion that working memory is related to and important for mathematical outcomes. An increasing number of studies confirm the strong relationship between working memory and mathematics performance and mathematical difficulties, or dyscalculia (e.g. Holmes & Adams, 2006; Passolunghi, Mammarella, & Altoè, 2008; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011). Dyscalculia can be defined as "a highly selective and specific deficit of a very basic capacity for understanding numbers, which leads to a range of difficulties in learning about number and arithmetic" (Butterworth, 2005, p. 455).

Working memory has also been hypothesized to play a significant role in early numeracy skills, such as counting and using quantities (Gersten, Jordan, & Flojo, 2005). Even at a young age, children constantly need to revise their stored information during the execution of numeracy tasks. Nevertheless, research focusing on working memory and the early development of mathematics in kindergarten is still scarce, despite the acknowledgment that early numeracy is important for later mathematical achievement (e.g. Jordan, Glutting, & Ramineni, 2010). Although only a limited number of studies (e.g. Espy et al., 2004; Kroesbergen, Van de Rijt, & Van Luit, 2007; Kyttälä, Aunio, & Hautamäki, 2009) examined the relationship between working memory and early numeracy skills in kindergarten specifically, their results show the importance of identifying working memory characteristics in the early development of mathematical cognition (Klein & Bisanz, 2000). For this reason, the two studies reported here will focus on (the development in) early numeracy of kindergartners with limited working memory skills.

In the studies about formal mathematical learning, both visual and verbal working memory types were repeatedly related to math achievement and development (e.g. Andersson & Lyxell, 2007; De Smedt et al., 2009; Krajewski & Schneider, 2009a). According to the review by Raghubar et al. (2010), no consensus can be reached about which component contributes most to math development, because an understanding of which aspects of working memory are deficient in children with math difficulties is obscured by the lack of precise knowledge of the particular strategies and processes that the child brings to bear on working memory tasks (possibly as a function of age and language) and by the lack of any theory that links these working memory processes to particular aspects of mathematical learning and performance. Swanson and Jerman (2006), however, after controlling for effects of several other variables stated that verbal working memory characterizes children with math difficulties. This conclusion and findings from other studies (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003) suggest that verbal working memory skills may be more generic in terms of supporting mathematical skills during primary school, whereas visuospatial working memory may be more specific to early mathematical learning. For example, Bisanz, Sherman, Rasmussen, and Ho (2005) found that visual spatial working memory was the best predictor of early math performance in kindergarten, but no longer in first grade. In the literature, this phenomenon is explained by the mental model hypothesis that has been applied to explain how visuospatial memory resources are linked to mathematical learning and performance (e.g. Huttenlocher, Jordan, & Levine, 1994). Conversely, Noël (2009) found a significant correlation between children's performance in counting and addition and measures of verbal working memory, but not with visuospatial working memory.

These contradictory results concerning the relation between the two types of working memory and mathematical achievement can be ascribed to the type of numerical tasks used in the studies. Whereas counting is a verbal exercise that is related to the vocabulary skills of children, other numeracy skills require more visual perception. The substantial differences in how numeracy skills are measured are mainly a consequence of the lack of an unequivocal definition of early numeracy (e.g. Gersten et al., 2005). In Study 1, early numeracy is defined as a multi-componential construct, consisting of verbal (i.e. logical operations, counting, the cardinality principle, and numerical representations) (Desoete & Gregoire, 2006; Nunes & Bryant, 1996) and nonverbal (i.e. numeral estimations) (e.g. Opfer & Siegler, 2007; Siegler & Booth, 2004) skills that can be operationalized into nine different early numeracy components (Kleemans, Segers, & Verhoeven, 2011).

Although research has shown a strong relationship between working memory and early numeracy achievement, less is known about the performance of kindergartners with limited working memory skills in verbal and nonverbal early numeracy tasks. Insight in the performance of this specific target group can be of contributable value to general knowledge about the gaps which children with very low working memory abilities experience in their early math learning. It can be expected that children with difficulties in verbal working memory experience problems in verbal mathematical tasks, such as reciting the counting row, but score appropriately on nonverbal early numeracy tasks. Children with limited visual working memory skills can be expected to struggle with visual numeracy tasks containing number symbols, but not verbal tasks.

In Study 2 the triple code model of Dehaene (1992, 2001) is used to define and operationalize early numeracy, in order to focus on the numerical aspects of early numeracy in more detail, and to clarify specific gaps in children's limited working memory skills. The model distinguishes three different types (so-called codes) for number representations; the analog magnitude code (semantic knowledge about the proximity and relative size of quantities), the auditory verbal code (the ability to enumerate the counting row), and the visual code (Arabic representations). The preverbal analog code develops first and can be measured as early as the first months of life (Dehaene, 2001). This suggests that children have an innate understanding of numerical magnitudes (Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004). Increasing experience with verbal numerical skills and with visual symbols during early childhood develops early math competence. New verbal or symbolic knowledge is gradually integrated with existing nonverbal knowledge, resulting in more complex cognitive representations in which number words are connected to quantity representations (Dehaene, 2001; Krajewski & Schneider, 2009b; Mundy & Gilmore, 2009). Then, children develop linear representations of these numbers, such that each number is one more than the one that comes before it and one fewer than the one that comes after it (Siegler & Booth, 2004). Several studies have demonstrated that children use these more advanced abilities in numerical estimation tasks (Whyte & Bull, 2008), and that accurate number-to-quantity representations are necessary for more advanced math learning (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegler & Opfer, 2003).

The two studies reported in this article were designed to compare skills of children with and without limited working memory in their development of early numeracy skills, numerical representations and the contributions of these representations to number line estimation. Similarly to the study by Alloway et al. (2009), both Study 1 and Study 2, six months apart, involved the identification of the verbal and visual working memory of a large sample of kindergarten children via routine screening of four standardized tests. In each study, children with very low working memory skills (below the fifteenth percentile) were selected and then classified into three groups: (1) children with limited verbal working memory skills, (2) children with limited visual working memory skills, and (3) children with limited working memory skills in both verbal and visual working memory. Then, in each study, a random sample was taken from all remaining children to represent (4) control children with typically developing working memory skills. Therefore, in each study a classification of four separate groups was made. The classifications of Study 1 and Study 2 partially overlapped, because they were based on screening at two different time points.

Study 1 was used to examine early numeracy skills throughout kindergarten in a sample of children aged four to five with limited working memory skills. The selected children completed a standardized early numeracy test including nine different verbal and nonverbal aspects of early numeracy at two time points in kindergarten with 12 months in between, in order to investigate to what extent and in which aspects children with specific limited working memory skills and children with typically developing working memory skills differed in their development of both verbal and nonverbal early numeracy skills. Study 2 was also designed to examine whether children with limited working memory skills differed in mastering specific numerical skills representing the three codes from the triple-code model (Dehaene, 1992), and whether the contributions of these representations to number line estimation differed between the four groups.

In both studies, it was expected that the control children would perform better than the children with very low working memory scores in the other three groups, because research shows that working memory ability is significantly associated with early numeracy skills (e.g. Espy et al., 2004; Kroesbergen et al., 2007; Kyttälä et al., 2009). Furthermore, it was expected that within the other three groups with specific limited working memory scores (verbal, visual or both) their specific working memory limitations would lead to failure in specific early numeracy tasks. More specifically, three expectations were formulated. First, children with limited visual working memory skills were hypothesized to have fewer problems in verbal numeracy tasks in Study 1 and in the verbal code in Study 2 (Bisanz et al., 2005). Second, children with limited verbal working memory skills were expected to have fewer problems with nonverbal tasks in Study 1, or the visual code in Study 2 (Kyttälä et al., 2003). And last, children who experienced problems in both systems of working memory are expected to be disadvantaged in terms of all numeracy tasks in both studies. With respect to the analog code in Study 2, no differences were expected between the three groups of children, because no specific working memory skills can be related to non-symbolic numerical skills.

Unlike the study by Alloway et al. (2009), in which the children were only selected on the basis of their performance on verbal working memory tasks, in the studies reported in this article, children were selected on the basis of their skills in both the verbal and visual system, for two reasons. First, their classification into three groups with limited working memory skills might provide useful insights for the debate on whether working memory capacity is captured by a domain-general component or domain-specific aspects (e.g. Alloway et al., 2006; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Kane et al., 2004). Research has shown that limited skills in working memory are particularly detrimental in tests of visual working memory (and central executive measures) and that this pattern is less consistent for verbal measures (Gathercole et al., 2004b). Second, this classification could provide evidence about what sort of difficulties children with restrictions in the two systems experience concerning early math learning.

General method for both studies

A total of 939 children (456 girls) with a mean age of 4.55 years (*SD* = 4.04 months) formed part of the screening sample for both studies. The children were attending the first year of kindergarten in 25 primary schools in rural or urban areas in the Netherlands. Participating schools were selected to reflect the national demographic profile of children in terms of, first, the number of children in the school and, second, the socio-economic background of the children, according to the classification system developed by the Dutch government that funds primary schools. Parental consent for all children participating was obtained. Socio-economic status (SES) was based on the educational attainment level of both parents on a seven-point scale ranging from one (only a few years of primary education at most) to seven (university degree), with a mean of 4.52 (*SD* = 1.73), because parental education is considered one of the most stable aspects of SES as it is typically established at an early age and tends to remain the same over time (Sirin, 2005).

All children were screened for very low working memory scores at two time points; halfway through the first year of kindergarten (Study 1) and at the end of this school year six months later (Study 2). All children were assessed by four working memory tasks, two visual and two verbal, from the Automatized Working Memory Assessment (AWMA; Alloway, 2007) and these scores were integrated in two latent factors (visual working memory and verbal working memory) by means of confirmatory factor analyses (see 3A.3, Study 1). Correlation analyses revealed significant correlations between the working memory scores at the two time points (visual: Pearson's $r = 0.49$; verbal: Pearson's $r = 0.65$).

STUDY 1

Method

Participants

Of the 884 children who were screened halfway through the first year of kindergarten (scores for 55 children were unobtainable owing to illness (flu season in winter), absence or failure to understand the task instructions), 190 children obtained scores below the fifteenth percentile in one or both working memory systems (owing to different distribution of the scores the exact cut-off percentiles were below but as close as possible to the fifteenth percentile: 14.1 for visual working memory and 12.0 for verbal working memory). The children were then classified into three groups: (1) 67 children with limited verbal working memory skills (*Verbal group*), (2) 86 children with limited visual working memory skills (*Visual group*), and (3) 37 children with limited skills in both verbal and visual working memory (*General group*). To match the group size of all selected children, a random sample ($N = 190$) from all remaining children was taken to represent children with typically developing working memory skills (*Typically achieving group*). The selected children were followed until halfway through the second year of kindergarten. Before this point, 14 children (3.86%) dropped out because of moving (10 children), or accelerating a grade (four children). These children were excluded from further analyses.

There was no significant association between gender and group classification ($\chi^2(3) = 3.50$, $p = .32$, $V = .10$), but there was a significant difference between the groups in their mean SES level ($F(3, 308) = 3.89$, $p = .00$) and their mean age ($F(3, 337) = 8.02$, $p = .00$). The mean SES level of the *Typically achieving group* was higher than the mean SES level of the *General group*. The *Typically achieving group* was significantly older than the three groups consisting of children with limited working memory skills. Therefore, both SES and age were included in the analyses as covariates to control for the group differences in SES and age. These analyses were conducted with an alpha of .05.

Procedure

The working memory screening procedure happened halfway through the first year of kindergarten (January 2011). The selected children completed a standardized early numeracy test at two time points 12 months apart (January 2011 and January 2012). The children were tested individually in a quiet area of the school for one or two 20–30-minute sessions, depending on selection. All tasks were obtained in a fixed sequence. All tests were administered by graduate students trained in education or psychology (university master's degrees).

Instruments

Working memory. Working memory ability was measured with four computer-based tasks (Dot Matrix, Odd One Out, Word Recall Forwards and Word Recall Backwards) from the Automatized Working Memory Assessment (AWMA; Alloway, 2007) that was translated and voice-recorded into Dutch. The AWMA has a stable construct validity and good diagnostic validity for children with low working memory skills. For children aged 4.5 and 11.5 years old the test-retest reliability of the four tasks was 0.83, 0.81, 0.76, and 0.74, respectively (Alloway et al., 2008). Each of the four working memory tasks started with a short practice session. All tasks were automatically terminated when a child gave three incorrect answers within a set of items of the same length.

First, the capacity of visuospatial storage component was assessed with *Dot Matrix*. The children were presented with a 4 x 4 matrix on the computer screen. A red dot shortly appeared in one of the boxes and the children had to point out the correct box. The test started with a block of one dot, building up to a block with a sequence of seven dots presented across the matrix. Each block consisted of six trials that were scored as incorrect when one of the boxes was omitted, when the sequence of boxes was incorrect, or when a box was recalled wrongly. When the first four trials within a block were recalled correctly, the child proceeded to the next block. The scores could range from zero to 28.

Second, the visuospatial processing component was measured by the *Odd One Out* task, in which children were asked to point out the odd shape in a row of three geometrical shapes, and to remember the location of this shape. Then three new shapes appeared. At the end of each trial three empty boxes appeared and the children were asked to point to the consecutive locations of the odd shapes. The test started with a set of one trial, building up to a block with a sequence of seven trials within a set. The number of correctly recalled trials was recorded for sets in which all items were recalled correctly. The scores could range from zero to 28.

Third, for the assessment of the verbal storage component, *Word Recall Forwards* was used. In this task, a recorded voice names a series of semantically unrelated one-syllable words, after which the child is asked to repeat the words in the same order. The string of words becomes more and more extensive (starting with one word and building up to a string of seven words) after a child has recalled several strings correctly and in the correct order. The number of correctly recalled series was recorded for sets in which all trials were recalled correctly. The scores could range from zero to 24.

Fourth, for the assessment of the verbal processing component, *Word Recall Backwards* was used. In this task, a recorded voice names a series of semantically unrelated one-syllable words, after which the child is asked to repeat the words in reverse order. The string of words becomes more and more extensive (starting with two words and building up to a string of seven words) after a child has recalled four strings correctly and in the correct order. The number of correctly recalled series was recorded for sets in which all trials were recalled correctly. The scores could range from zero to 24.

The scores for the four working memory tasks represent the number of correct answers given for these tasks. These scores can be considered as valid only if there are no extreme values identified (Tabachnick & Fidell, 2006). For that reason, univariate outliers – scores differing by three standard deviations or more from the mean – were converted into scores within the normal range (with a standard deviation of two or -2). This procedure was carried out for seven scores on Dot Matrix, one score on Odd One Out, nine scores on Word Recall Forwards, and no scores on Word Recall Backwards. In total the procedure was carried out for 1.78% of the working memory scores. Univariate outlier scores on the working memory scores can be explained by extremely poor and extremely good performances of individual children.

Each of the four working memory tasks represents a component of the model of Alloway et al. (2006). To confirm this model, confirmatory factor analyses (CFA) were performed by means of structural equating modeling (SEM) on the four working memory tasks. As is common in SEM, overall model fit is indicated by several fit indices, which each evaluate different aspects of the model. Here, the fit indices recommended by Blunch (2008) and Brown (2006) are reported: chi square (χ^2) with its *p*-value, comparative fit index (*CFI*), and root mean square error of approximation (*RMSEA*) with its p_{close}-value. Chi-square is a discrepancy measure between the current model and the saturated model, and should, therefore, be as low as possible, with a *p*-value that is as high as possible. *CFI* compares the fit of the model to the independence model and is good if *CFI* > 95 and acceptable if *CFI* > 0.90. *RMSEA* is a parsimony measure, favoring simpler models, and is good if < 0.05 and acceptable if < 0.08. Its p_{close}-value should be high. Two alternative models were tested. The first model was a model with all working memory tasks loading on a single factor. The second model was the model based on the distinction made by Alloway et al. (2006), with two latent factors: visual and verbal working memory, each latent factor having two indicators. These two models were compared and the better-fitting model was chosen for further analyses. From Table 7.1, it can be concluded that only the two-factor model, with one factor for visual and one factor for verbal working memory, was applicable with a good fit. The standardized factor loadings from the better-fitting two-factor model for the scores presented in Table 7.2 were used to compute individual factor scores for visual and verbal working memory that were used to screen the children for limited working memory skills.

Table 7.1 Fit indices for models for Study 1 with the two possible factor structures, with best fitting model in italics

	χ^2	*df*	*p*	*CFI*	*RMSEA*	P_{close}	*AIC*
1 factor: working memory	29.61	2	.00	0.95	0.13	.00	15966.63
2 factors: visual and verbal WM	*0.51*	*1*	*.47*	*1.00*	*0.00*	*.79*	*15939.53*

Note. WM = working memory.

Table 7.2 Standardized factor loadings CFA for Study 1

		Stand. fact. loading (*SE*)	Intercept (*SE*)	Residual variances (*SE*)	Correlation (*SE*)
Visual WM	Dot Matrix	.69 (0.03)	3.14 (0.08)	.53 (0.05)	
	Odd One out	.69 (0.03)	2.61 (0.07)	.55 (0.04)	.76** (0.04)
Verbal WM	Word Recall Forwards	.63 (0.03)	4.95 (0.12)	.61 (0.04)	
	Word Recall Backwards	.67 (0.04)	1.17 (0.04)	.56 (0.05)	

Note. WM = working memory. ** $p < .01$.

Early numeracy. The selected children completed the *Early Numeracy Test-Revised* (ENT-R; Van Luit & Van de Rijt, 2009) at two time points to measure early numeracy skills. The ENT-R is a 45-item standardized pencil-and-paper test for children between the ages of four and seven years old. The test consists of nine parts that are indicators of early numeracy. The components can be divided into eight verbal tasks (concepts of comparison, classification, correspondence, seriation, use of numerals, synchronized and shortened counting, resultative counting, and general understanding of numbers) and one non-verbal task (estimation). Each component contains five consecutive items. The total of correct answers (zero to 45) was converted into competence scores (one to 100) that were used in the analyses. The reliability coefficient of the test is good ($\alpha = .94$). A principal component analysis (PCA) with varimax rotation on the nine components revealed one factor, explaining 44.93 percent of the variance. At the next time point, again one factor was revealed, explaining 41.25 percent of the variance. Prior to the two PCA, the Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) measure were used to test whether factor analysis is appropriate for these data. The Bartlett's Test of Sphericity was significant for both time points (first time point: $\chi^2(36) = 2428.80$, $p = .00$; second time point: $\chi^2(36) = 1963.59$, $p = .00$), which means that there are some relationships between the variables, and the KMO measures had values of respectively 0.91 and 0.90, which both fall into the large range (Hutcheson & Sofroniou, 1999). On the basis of both statistics it can be concluded that factor analyses are appropriate for both time points. Reliability analyses revealed good internal consistency of the factor for the first time point ($\alpha = .84$) and the second time point ($\alpha = .82$).

Results

Study 1 is designed to investigate to what extent children with (specific) limited working memory skills and children with typically developing working memory skills differ in their development of early numeracy skills Table 7.3 presents for all four groups the mean scores for the total score on the early numeracy test and the subscores on all nine components. The statistical analyses were carried out in two steps. First, the general early numeracy development of the four groups was investigated with an ANOVA for repeated measures. The analysis was carried out to examine whether the total early numeracy score did indeed differ between the two time points. The four groups were added as independent variable. Second, to examine more closely the early numeracy development of the four groups, nine ANOVAs for repeated measures were used with each component of the test as a dependent variable. Again, the four groups were added as independent variable. Post hoc analyses with Bonferroni adjustment were carried out to correct for an experiment-wise error rate. Only the significant results are reported. The overall results of the analyses are presented in Table 7.3.

Most importantly, these results show a significant effect for time in all analyses, meaning that the children improve on their total early numeracy ability and all sub-skills between the first and the second time point, one year later. Furthermore, in all analyses a significant effect for group was found. The descriptive statistics in Table 7.3 show a similar pattern for the total early numeracy score and all sub-skill scores; the *Typically achieving group* performed best, followed by the *Visual group*, then the *Verbal group*, with the *General group* performing lowest in the tests. Post hoc analyses revealed that for all skills except comparison and counting the score of the *Typically achieving group* was significantly higher than the scores of the three groups with (specific) limited working memory skills. The *General group* performed worse than the other three groups on all skills except for seriation, counting, synchronous counting and resultative counting. There the *Verbal Group* performed just as poorly as the *General group*.

On all tasks the *Verbal group* performed less well than the *Visual group*, but significance was only reached for two domains: counting and applying number knowledge. The development of the four groups differed on four sub-skills: comparison, correspondence, counting and applying number knowledge. A more detailed look at the analyses showed a faster development of the *Verbal group* compared with the other three groups on comparison and correspondence. For counting and applying number knowledge, the *General group* and the *Verbal group* developed less fast than the *Visual group* and the *Typically achieving group*.

Preliminary analyses revealed significant correlations between SES and age knowledge and almost all early numeracy components. Therefore, the ten analyses were conducted again with these two variables taken into account as a covariate. Compared with the analyses without covariates, results show the disappearance of all interaction effects, the disappearance of the time effect on all components except comparison and correspondence, and the disappearance of group effect on numerical estimations. SES was not a significant covariate in the analyses for counting, synchronous counting and estimation, and age was not a significant covariate for numerical estimations. Results found for the total early numeracy score were no different.

Table 7.3 Early numeracy test scores and results of the repeated measures ANOVA for the four groups

Group		General			Verbal			Visual			Typically			Time effect			Group effect			Interaction effect		
	T	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*F*	*df*	η^2	*F*	*df*	η^2	*F*	*df*	η^2
Total early numeracy	1	36	7.58	3.56	67	10.27	5.51	86	11.81	6.48	188	16.57	7.24	919.18**	1, 361	.72	37.50**	3, 361	.24	2.23	3, 361	.02
	2	34	17.76	6.81	64	23.30	6.14	82	25.49	7.36	186	28.84	6.85									
Verbal tasks																						
Comparison	1	36	2.59	1.21	67	2.86	1.38	86	3.22	1.39	188	3.74	1.24	185.39**	1, 356	.34	15.13**	3, 356	.11	4.73**	3, 356	.04
	2	34	3.76	1.05	64	4.42	0.75	82	4.46	0.71	186	4.51	0.75									
Linking quantities	1	36	0.62	0.70	67	1.08	1.00	86	1.23	0.90	188	1.72	0.89	222.11**	1, 356	.38	20.73**	3, 356	.15	0.70	3, 356	.01
	2	34	1.71	0.91	64	2.36	1.01	82	2.49	0.92	186	2.74	1.13									
Correspondence	1	36	1.29	0.76	67	1.56	0.86	86	2.05	1.18	188	2.56	1.11	343.90**	1, 356	.49	19.13**	3, 356	.20	3.62*	3, 356	.03
	2	34	2.68	1.01	64	3.55	1.01	82	3.46	1.03	186	3.92	1.00									
Seriation	1	36	0.62	0.85	67	0.71	0.92	86	0.91	1.18	188	1.81	1.41	398.38**	1, 356	.53	28.71**	3, 356	.20	2.14	3, 356	.02
	2	34	1.94	1.37	64	2.77	1.32	82	2.77	1.35	186	3.59	1.22									
Counting	1	36	0.18	0.46	67	0.26	0.56	86	0.67	1.01	188	0.89	1.03	227.87**	1, 356	.39	20.08**	3, 356	.15	2.84*	3, 356	.02
	2	34	1.21	1.15	64	1.38	1.18	82	2.22	1.37	186	2.42	1.36									
Synchronous counting	1	36	0.44	0.71	67	0.71	0.76	86	0.73	0.89	188	1.45	1.23	240.29**	1, 356	.40	19.46**	3, 356	.14	1.37	3, 356	.01
	2	34	1.56	1.13	64	2.25	1.56	82	2.50	1.42	186	2.95	1.33									
Resultative counting	1	36	0.38	0.60	67	0.64	0.91	86	0.87	1.10	188	1.52	1.24	301.20**	1, 356	.46	22.96**	3, 356	.16	0.92	3, 356	.01
	2	34	1.56	1.21	64	2.34	1.28	82	2.57	1.47	186	3.08	1.25									
Applying number knowledge	1	36	0.85	0.78	67	0.95	0.81	86	1.06	1.01	188	1.60	1.13	159.60**	1, 356	.31	24.63**	3, 356	.17	4.39**	3, 356	.04
	2	34	1.76	1.30	64	1.88	1.18	82	2.68	1.46	186	3.10	1.29									
Nonverbal tasks																						
Numerical estimations	1	36	0.59	0.82	67	0.97	1.04	86	1.05	1.21	188	1.37	1.27	134.59**	1, 356	.27	9.00**	3, 356	.07	0.47	3, 356	.00
	2	34	1.59	1.23	64	2.38	1.24	82	2.32	1.47	186	2.54	1.24									

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

Conclusion and discussion

In Study 1, it was examined whether the early numeracy development of children with (specific) limitations in their working memory resources was comparable to the early numeracy development of children with typically achieving working memory skills. It can be concluded that children with limited working memory skills experience difficulties in general early numeracy, and are therefore at risk of developing serious mathematical learning difficulties during primary school. This is in line with previous research on the predictive relation between working memory and early numeracy (Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Zheng, Swanson, & Marcoulides, 2011), and supports the implication that working memory is a useful measure to signal children at risk of developing math learning difficulties, or even disabilities (e.g. Toll et al., 2011). Fortunately, the difference in performance level compared with typically achieving children does not grow over time. It would be interesting to investigate whether all children, with or without limited working memory skills, profit equally from support (curriculum and instruction) throughout kindergarten education. Therefore, further research should focus on the stimulation of early numeracy skills of children with limited working memory skills with specific early numeracy training to explore whether it is possible to bridge the gap between children with typically developing working memory systems and atypically developing children.

Comparing the groups based on their specific restrictions, it was found that the children with limitations in both working memory systems have the most difficulties in performing early numeracy tasks. This can probably be ascribed to the fact that these children have a working memory capacity that is weak or limited, and therefore cannot fall back on working memory ability from another system, something that is possible for children with restrictions in only one working memory system. This could explain why no difference was found between children with limited verbal working memory skills and children with limited visual working memory skills. With regard to specific domains of early numeracy, in almost all domains a similar pattern was found; typically achieving children performed better than children with limited working memory resources. The hypothesis that the children with limited verbal working memory skills would be at a disadvantage in more verbal domains but would perform better in the nonverbal domain is not supported. Also, the finding that visual spatial working memory was the best predictor of early math learning (Bisanz et al., 2005), could not be confirmed, because in all tasks the children with limited visual working memory skills performed better than children with limited verbal working memory skills. Consequently, the mental model hypothesis (e.g. Huttenlocher et al., 1994) could not be endorsed.

STUDY 2

Method

Participants

Of the 937 children who were screened at the end of the first year of kindergarten (two children were missing owing to illness), 200 children obtained scores below the fifteenth percentile in one or both working memory systems (the exact cut-off percentiles were below but as close as possible to the fifteenth percentile: 14.4 for visual working memory and 12.6 for verbal working memory). A similar classification method to that in Study 1 was used, likewise resulting in four groups: (1) 66 children with limited verbal working memory skills (*Verbal group*), (2) 82 children with limited visual working memory skills (*Visual group*), (3) 52 children with limited skills in both verbal and visual working memory (*General group*), and (4) 200 children with typically developing working memory skills (*Typically achieving group*). The selected children were tested again halfway through the second year of kindergarten. Before this point, 19 children (4.75%) dropped out because of moving (13 children), or accelerating a grade (six children). Nine of these children were also selected in Study 1. These children were excluded from further analyses.

There was no significant association between gender and group classification ($\chi^2(3) = 5.78$, $p = .12$, $V = .12$), but there was a significant difference between the groups in their mean SES level ($F(3, 313) = 4.98$, $p = .00$) and their mean age ($F(3, 394) = 11.80$, $p = .00$). The mean SES level of the *Typically achieving group* and of the *Visual group* was higher than the mean SES level of the *General group*. The *Verbal group* and the *Typically achieving group* were significantly older than the *General group*. Furthermore, the *Typically achieving group* was older than the *Visual group*. Therefore, both SES and age were included in the analyses as covariates to control for the group differences in SES and age. These analyses were conducted with an alpha of .05.

Table 7.4 presents the overlap between the classifications from Study 1 and Study 2. Of the 380 children selected in Study 1, 170 children (44.73%) were selected again in Study 2. Of the 190 children classified because of their limited working memory skills in Study 1, 83 children (43.86%) were selected again in Study 2. Of the three groups the percentages were respectively 34.88% (*Visual group*), 43.28% (*Verbal group*), and 64.86% (*General group*). There was a significant association between having limited working memory skills halfway through the first year of kindergarten and having limited

Table 7.4 Overlapping children classification Study 1 and classification Study 2

	Study 2					
Study 1	Visual group	Verbal group	General group	Typically achieving group	Not selected / missing	Total
Visual group	13	7	10	10	46	86
Verbal group	2	20	7	10	28	67
General group	5	4	15	3	10	37
Typically achieving group	13	10	3	38	126	190
Not selected / missing	49	25	17	139	329	559
Total	82	66	52	200	539	939

working memory skills six months later at the end of the first year of kindergarten, $\chi^2(1) = 71.20$, $p = .00$, $V = .28$.

Procedure

The working memory screening procedure happened at the end of the first year of kindergarten (June 2011). The selected children completed four numerical tasks six months after screening (January 2012). The procedure was identical to the one used in Study 1.

Instruments

Working memory. Working memory ability was measured with four computer-based tasks (Dot Matrix, Odd One Out, Word Recall Forwards and Word Recall Backwards) from the Automatized Working Memory Assessment (AWMA; Alloway, 2007). The four tasks were identical to the ones used in Study 1. The same outlier procedure as described in Study 1 was carried out for nine scores on *Dot Matrix*, no scores on *Odd One Out*, eighteen scores on *Word Recall Forwards*, and one score on *Word Recall Backwards*. In total the procedure was carried out for 2.36% of all working memory scores.

Each of the four working memory tasks in Study 2 represents a component of the model of Alloway et al. (2006). Confirmatory factor analyses (CFA), similar to the ones in Study 1, were performed. From Table 7.5, it can be concluded that only the two-factor model, with one factor for visual and one factor for verbal working memory, was applicable with a good fit. The standardized factor loadings from the better-fitting

Table 7.5 Fit indices for models for Study 2 with the two possible factor structures, with best fitting model in italics

	χ^2	*df*	*p*	*CFI*	*RMSEA*	P_{close}	*AIC*
1 factor: working memory	39.46	2	.00	0.94	0.14	.00	17049.22
2 factors: visual and verbal WM	*0.32*	*1*	*.57*	*1.00*	*0.00*	*.85*	*17012.08*

Note. WM = working memory.

Table 7.6 Standardized factor loadings CFA for Study 2

		Stand. fact. loading (*SE*)	Intercept (*SE*)	Residual variances (*SE*)	Correlation (*SE*)
Visual WM	Dot Matrix	.66 (0.04)	3.56 (0.09)	.56 (0.05)	
	Odd One out	.63 (0.03)	2.76 (0.07)	.61 (0.04)	.73** (0.04)
Verbal WM	Word Recall Forwards	.64 (0.03)	5.78 (0.14)	.60 (0.04)	
	Word Recall Backwards	.74 (0.03)	1.55 (0.05)	.45 (0.05)	

Note. WM = working memory. ** $p < .01$.

two-factor model for the scores presented in Table 7.6 were used to compute individual factor scores for visual and verbal working memory that were used to screen the children for limited working memory skills.

Numerical skills. The selected children completed a total of six tasks to measure their numerical skills. Except for the counting task, all tasks were computer-based.

First, a quantity comparison task was administered to test the children's ability to discriminate between quantities and to measure the analog magnitude code of Dehaene's triple-code model. In this task, the child was asked to compare two arrays with dots and had to indicate the array with the highest number of dots. The dots varied not only in number but also in size (Barth et al., 2006; Gebuis, Cohen Kadosh, De Haan, & Henik, 2009). To control for non-numerical parameters (such as dot size, covered surface, density) three conditions could be distinguished: (1) congruent condition in which the area with the largest number of dots was also physically larger, (2) incongruent condition in which the area with the largest number of dots was physically smaller and (3) a neutral condition in which the physical size of the dots in both areas was the same but the number varied. In each condition 10 trials were presented with the amount of dots ranging from one to 100. The dependent measure was the number of items (30 in total) solved correctly. The child received two practice items, but no prompts were given during the actual task. Although few studies reported the reliability of the dot comparison task, the task is frequently used as a measure of quantity discrimination (De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Malofeeva, Day, Saco, Young, & Ciancio, 2004). The internal consistency of this comparison measure was good in this study (α = .87), and in another study as well (α = .93) (Boonen, Kolkman, & Kroesbergen, 2011).

Second, an oral counting task was administered to test the children's ability to enumerate the counting row. Two components (use of numerals and synchronized and shortened counting) from the Early Numeracy Test-Revised (ENT-R; Van Luit & Van de Rijt, 2009) were used to measure the auditory verbal code of Dehaene's triple-code model. The items contained children's skills at counting forwards and backwards, use of the ordinals (first, second, etc.), matching the numbers of the counting row with the numbers of a certain number of objects (both structured and unstructured collections) and understanding of cardinality. The internal reliability coefficient across all subtest items of the ENT-R was high (α = .93), and the reliability of the subscales used in the study was sufficient (α = .68).

Third, two number-naming tasks were administered to measure children's knowledge of the numbers from one to 10 (10 items in total) and one to 100 (12 items in total) and to measure the visual code of Dehaene's triple-code model (1992). In each task, a number of symbols were presented in randomized order and the number of correctly identified symbols in total (of the two tasks) was used as a total score. To obtain a robust measure of number naming, the scores on these two tasks were aggregated into one score (M = 14.60, SD = 3.54). The internal consistency of this task was good in this study (α = .81) and in other studies (α = respectively .72 and .94) (Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Malofeeva et al., 2004).

Fourth, two number-line tasks were administered to measure children's ability to map symbols to a corresponding position on a number line from one to 10 (eight items in total) or from one to 100 (10 items in total) (Booth & Siegler, 2006; Laski & Siegler, 2007). In each task, the child was asked to estimate the position of a given number in randomized order (in the range from one to 10 or one to 100) on a horizontal line. Linear fit scores (r^2) were computed by fitting the answers of each child to a linear curve (Geary et al., 2008). To obtain a robust measure of number line estimation, the linear fit scores on these two tasks were aggregated into one score (M = 0.56, SD = 0.18). Sufficient reliability was found for this task (α = .69).

Results

Study 2 was designed to examine whether children with limited working memory skills differ in mastering specific numerical skills representing the three codes from the triple-code model (Dehaene, 1992), and whether the contributions of these representations to number line estimation differ between the classified groups. Table 7.7 presents the descriptive statistics for the four tasks. For the quantity comparison task (the analog code), one-sample t-tests showed significant differences between chance level accuracy and the actual accuracy rate, indicating that children performed well above chance level (t = 93.61; p = .00). Descriptive statistics in Table 7.7 show a similar pattern for scores in the four tasks; the *Typically achieving group* performing best, followed by the *Visual group*, then the *Verbal group*, and the *General group* performing worse on the tasks.

To meet the objective of Study 2, three steps were taken in the process of analysis. The first step was to explore group differences in the three numerical codes and in the performance of number-line estimation. It was tested whether SES level and age were significant covariates in the analyses. Because they turned out not to be, and inclusion revealed similar results, both SES level and age were excluded as covariates. The results of the multivariate tests of variance without covariates are presented in Table 7.7. Post hoc analyses with Bonferroni adjustment were carried out to correct for experiment-wise error rate. Only the significant results are reported.

First, for the analog code, the post hoc analyses revealed significantly lower scores for the *General group* compared with the other three groups. Then, for the verbal code, the *Typically achieving group* scored significantly higher than the other three groups. The *General group* scored similarly to the *Verbal group*, but less well than the *Visual group*. Against expectations, the scores of the *Verbal group* and the *Visual group* did not differ significantly. Third, for the visual code, the *Typically achieving group* scored significantly higher than the *General group* and the *Verbal group*, and the *Visual group* scored significantly higher than the *General group*. Last, in number-line estimation, the scores of the *General group* and the *Verbal group* were similar, but lower than the score of the Visual group that was, in turn, lower than the score of the *Typically achieving group*.

In the next step, the correlations between the number-line estimation and the different numerical codes were investigated for each group separately (Table 7.8). Note that for all groups, significant correlations were found with the visual code and that significant correlations with all codes were found only for the *Verbal group*.

Finally, for each group a regression analysis was carried out to explore the explaining value of the three numerical codes in number-line estimation ability. These

Table 7.7 Test scores on three numerical codes and the number line estimation tasks, and results of the multivariate analysis of variance for the four groups

Groups	General			Verbal			Visual			Typically			Group effects		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*F*	*df*	η^2
AC	48	23.00	4.96	65	25.34	3.72	80	25.81	3.25	188	26.68	3.03	14.23**	3, 375	.10
VEC	48	2.65	1.63	65	3.28	1.89	80	3.91	2.09	188	5.41	2.35	30.74**	3, 375	.20
VIC	48	11.74	4.75	65	13.11	4.50	80	14.19	3.78	188	15.40	3.03	15.01**	3, 375	.11
NLE	48	0.35	0.20	65	0.43	0.19	80	0.52	0.18	188	0.60	0.15	35.14**	3, 375	.22

Note. AC = analog code, VEC = verbal code, VIC = visual code, NLE = number line estimation.
** $p < .01$.

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Table 7.8 Correlations between the number lines estimation task and the three numerical codes for all four groups separately

Number line estimation	Analog code	Verbal code	Visual code
General group	.10	.18	.43**
Verbal group	.36**	.34**	.47**
Visual group	.19	.31**	.58**
Typically achieving group	.03	.38**	.28**

** $p < .01$.

analyses examined whether number-line estimation could be explained by analog, verbal or visual number representations and whether this pattern differed between the four groups. To test the relative effect of the three codes on the number-line estimation, all three tasks were entered together. Table 7.9 shows the results of the four regression analyses. In all groups, the visual code showed a significant contribution to number-line estimation. For the *General group* 18% of the variance could be explained by the visual code, whereas for the *Verbal group* and the *Visual group* respectively 30% and 35% could be explained by the visual code. For the *Typically achieving group*, the verbal code was also a significant predictor of number-line estimation skills. Together with the visual code it explained 19% of the variance (Table 7.9).

Conclusion and discussion

Study 2 was designed to compare the children's performance on the three number representations from the triple-code model of Dehaene (1992). For the first developing ability to use quantities, i.e. the analog code, the children with restrictions in only one working memory system did not have a disadvantage in comparison with the typically achieving children. Only the children with both limited verbal and limited visual resources performed badly. For the verbal code, however, it can be concluded that counting skills are mastered better by typically achieving children. Whereas it was expected that children with limitations in the visual part of their working memory would perform less well on the visual code, this expectation was contradicted by the current results. These children performed almost the same as children without limited working memory skills.

Table 7.9 Results of regression analyses; explaining number line estimation separately for the four groups

	B	*SE*	β	*t*	*p*	R^2	*F*
General group						.18	3.13*
Constant	.14	0.14		1.02	.32		
Analog code	.00	0.01	.01	0.07	.94		
Verbal code	.02	0.02	.00	0.00	.99		
Visual code	.02	0.01	.43	2.73	.01		
Verbal group						.30	8.56**
Constant	-.10	0.15		-0.71	.48		
Analog code	.01	0.01	.21	1.87	.07		
Verbal code	.02	0.01	.17	1.49	.14		
Visual code	.02	0.01	.36	3.06	.00		
Visual group						.35	13.49**
Constant	.07	0.14		0.50	.62		
Analog code	.00	0.01	.05	0.48	.64		
Verbal code	.01	0.01	.08	0.79	.43		
Visual code	.03	0.01	.54	5.18	.00		
Typically achieving group						.19	14.29**
Constant	.38	0.10		3.84	.00		
Analog code	-.00	0.00	-.05	-0.72	.47		
Verbal code	.02	0.01	.35	5.02	.00		
Visual code	.01	0.00	.22	3.12	.00		

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

For all groups, it can be concluded that adequate knowledge of the Arabic number symbols up to 10 and up to 100 is crucial for the execution of an estimation task, but mastering the analog code does not contribute to this. This is in line with Rouselle and Noël (2007), who found that children with mathematical learning disabilities have difficulty in accessing number magnitude of symbols rather than in processing numerosity per se. Only when children have a thorough mastering of number symbols (the visual code) do the other codes (analog and verbal) start to play a role in estimation skills. From the typically achieving children, it can be concluded that first mastering the number symbols and then knowing the counting sequence contributes most to the execution of estimation skills on linear number lines. This is in line with previous research suggesting that large, approximate numerosity representations become linked to number words around the time children learn to count those words reliably (Lipton & Spelke, 2005). At that specific point, the analog code, i.e. the ability to use and interpret quantities, has already been mastered and therefore does not contribute to the estimation skills of young children.

General discussion

The main objective of the present study was to compare the early numeracy skills of kindergartners with limited working memory skills with the early numeracy skills of typically developing kindergartners. To meet this objective, two related studies were carried out. For both studies, a large sample of kindergartners was screened on their working memory abilities. In each study, the kindergartners with limited working memory skills were classified into three groups based on the specificity of the restrictions in their working memory skills. Consequently it was possible to compare children with problems in verbal working memory, children with problems in visual working memory, and children with more general problems in both verbal and visual working memory. In the next step in both studies, a control group was added to the classification, representing children who perform typically on the working memory tasks. Therefore, the classifications of Study 1 and Study 2 partially overlapped, because they were based on the screening of the same sample at two different time points.

From Study 1 it became clear that children with limited working memory skills experience difficulties in general early numeracy, and also the development of a number of specific early numeracy skills is slower than the development of children with typical working memory skills. This confirms the hypothesis that there is a predictive relation between working memory and early numeracy (Meyer et al., 2010; Zheng et al., 2011), and that children with limited working memory skills are therefore at risk of developing serious mathematical learning difficulties during primary school. This supports the implication that working memory is a useful measure to signal children at risk of developing math learning difficulties or even disabilities (e.g. Toll et al., 2011).

Study 2 was carried out to focus in more detail on the numerical aspects of early numeracy. From this study, against expectations, it can be concluded that children with specific limitations in one working memory system do not experience problems in specific numerical skills (i.e. verbal working memory limitations do not lead to deficits in mastering the counting sequence or other verbal number skills, and visual working memory limitations do not lead to deficits in mastering visual number symbols). Children with limitations in both working memory systems, however, do experience more problems in the different numerical tasks. Furthermore, Study 2 confirms the findings from previous studies (Lipton & Spelke, 2005) that, first, only when children have a thorough mastering of number symbols (the visual code) do the other codes (analog and verbal) start to play a role in estimation skills and, second, that large, approximate numerosity representations become linked to number words around the moment children learn to count those words reliably.

Although both studies were designed to focus on a different area in early numeracy, there are some common results. For example, one conclusion that was drawn in both studies is that children with limited working memory skills score worse in verbal early numeracy tasks than their peers with typically working memory. This is in line with a study by Noël (2009) on verbal skills such as counting and addition. In that study, however, the correlation was only significant for verbal working memory and not for measures of visual working memory. Another important finding from both studies concerns children with limited verbal working memory skills. In both studies, it was expected that these children would be at a disadvantage in verbal early numeracy tasks, but would perform better in the nonverbal or the visual domain. This was not, however, supported by either study. Another conclusion, based on both studies, is the weakness of the performances of children with limitations in both working memory systems compared with their peers. This conclusion implies that this specific group of children merits special attention, because they are at high risk of developing severe problems with numerical challenges.

With regard to the results from the classifications in Study 1 and Study 2 it is worth mentioning that more than half of the children identified in Study 1 as having limited working memory skills no longer met the criterion in Study 2. This seems to indicate that working memory skills in young children, and especially limited ones, are exposed to an amount of fluctuation, suggesting that deficits at this age are not yet stable. Further research is necessary to examine this phenomenon and to search for possible explanations on the child and environmental level.

A limitation of the present study is the lack of fluid and/or crystallized intelligence (IQ) measures. An IQ measure was not included in this study, because many studies on working memory show high correlations between IQ and working memory abilities (e.g. Colom et al., 2003; Conway et al., 2002; De Smedt et al., 2009; Krajewski & Schneider, 2009a; Oberauer et al., 2005; Schuchardt et al., 2010) and IQ does not always add explained variance when explaining differences in early numeracy (Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009). Another important reason for the absence of an IQ measure has to do with the number of tests that were administered per measurement. Because most of the children were only 4-year-olds, and had just entered kindergarten when the study started, adding another test could have led to participant fatigue. There are also interesting studies showing the unique contribution of IQ in terms of the relationship between working memory and specific scholastic skills (e.g. Mäehler & Schuchardt, 2009), or showing only an average correlation between working memory and general intelligence (Ackerman, Beier, & Boyle, 2005). In future studies, when the size of the test battery allows another test, it is recommended that researchers include a general intelligence measure in addition to working memory.

Within the present study the selection of the children was based on a cut-off score of 15% of the total sample instead of a norm-based criterion. The large sample in this study allowed a percentile cut-off as selection method, but in future studies it would be interesting to use norm scores based on a standardized test battery.

To summarize, this study contributes to the knowledge that children with limited working memory skills are less good at mastering and developing early numeracy skills. This implies that using working memory tests to screen children at risk for math learning disabilities could be useful in showing a possible reason for low math performance. Further research is necessary to investigate whether these children could be helped by stimulation of their early numeracy skills within an educational setting.

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Accelerating the early numeracy development of kindergartners with limited working memory skills through remedial education

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Abstract

Background: Young children with limited working memory skills are a special interest group among all children that score below average on early numeracy tests. This study examines the effect of accelerating the early numeracy development of these children through remedial education, by comparing them with children with typical working memory skills and early numeracy abilities below average. **Method:** Selected from a sample of 933 children, children with early numeracy ability below average are assigned into four groups: two intervention groups with limited working memory skills (IL-group) or typical working memory skills (IT-group), and two control groups with limited working memory skills (CL-group) or typical working memory skills (CT-group). All four groups were followed for a period of 1.5 years. Four measurements were carried out. **Conclusion:** The remedial program proved to be similarly effective for the IL-group and the IT-group. The findings are discussed in the light of several limitations and implications.

Introduction

A child requires particular skills to start learning basic mathematical calculations in first grade, such as (verbal) counting, knowing the number symbols, subitizing small quantities, discerning number patterns, and comparing numerical magnitudes and estimating quantities (Desoete, Ceulemans, De Weerdt, & Pieters, 2010; Fuchs et al., 2010; Gersten, Jordan, & Flojo, 2005; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). For many children, acquiring these early numeracy abilities before first grade does not develop spontaneously. As a consequence, children with low early numeracy abilities that do not receive remedial assistance during kindergarten already trail behind at the start of grade one, and are not able to catch up during primary school with their typically developing peers when it comes to conventional mathematical knowledge (Jordan, Glutting, & Ramineni, 2010; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011) and fluency (Locuniak & Jordan, 2008).

Children with limited working memory skills and low early numeracy are a special interest group among children with low early numeracy abilities. Although only a few studies (e.g., Espy et al., 2004; Kroesbergen, Van de Rijt, & Van Luit, 2007) examined specifically the relationship between working memory and early numeracy skills in kindergarten, their results show the importance of identifying working memory characteristics in the early development of mathematical cognition (Klein & Bisanz, 2000; Kyttälä, Aunio, & Hautamäki, 2009). There is no consensus, however, as to whether verbal or visual working memory is a better predictor of math development, since both components of working memory have been repeatedly related to math achievement and development (e.g., De Smedt et al., 2009; Krajewski & Schneider, 2009). Noël (2009), for example, found a significant correlation between children's performance in counting and addition and measures of verbal working memory, but not with measures of the visuo-spatial working memory.

A strong relation is found between (weak) intelligence and (limited) working memory skills (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Schuchardt, Gebhardt, & Mäehler, 2010). Thus, working memory tasks highly correlate with performances on IQ tests (Alloway & Passolunghi, 2011), although working memory tasks seem to measure something different from general ability tests (Cain, Oakhill, & Bryant, 2004). While IQ tests measure knowledge that the child has already learned, working memory tasks are more a pure measure of a child's learning potential (Alloway & Alloway, 2010). Limited working memory skills have proven to be a risk factor for children's underperformance on national curriculum assessments at seven years of age and their working memory skills (Gathercole, Pickering, Knight, & Stegmann, 2004), as well as educational underachievement for school children across the primary school years (Alloway, Gathercole, Kirkwood, & Elliott, 2009). This implies working memory, instead of more general abilities test, is a good prediction measure to identify children at risk of developing learning difficulties at an early stage and the limited working memory skills can be compared with children with (mild) intellectual disabilities (Schuchardt et al., 2010; Schuchardt, Maehler, & Hasselhorn, 2011; Van der Molen, Van Luit, Jongmans, & Van der Molen, 2009).

Within the scientific educational field, various studies examined the effectivity of numeracy programs or curricula for children in kindergarten (Clements & Sarama, 2007; Greenes, Ginsburg, & Balfanz, 2004; Griffin, 2004; Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005; Krajewski, Nieding, & Schneider, 2008; Sarama & Clements, 2004). Some studies focused especially on at-risk children from low economic status families (Dyson, Jordan, & Glutting, 2011) or with low early numeracy ability (Van de Rijt & Van Luit, 1998; Van Luit & Schopman, 2000). The results of these studies confirm the importance of effective numeracy instruction and that extra assistance in kindergarten is especially important for children with low early numeracy performance, in order to start math education in first grade without already trailing behind their peers.

Evidence from experimental and educational studies of typically developing children supports the idea that mathematical ability is not unitary but constituted of different components (e.g., Dowker, 1998). The intervention programs mentioned above cover several skills that are necessary in preparatory math education. In general, eight aspects of early numeracy can be distinguished: reasoning skills (i.e., classification, comparison, and seriation; Adhami, Johnson, & Shayer, 1998; Kidd, Pasnak, Gadzichowski, Ferral-Like, & Gallington, 2008; Pasnak et al., 2009), counting skills (i.e., acoustic counting, synchronic counting, resultative counting; Askew, Bibby, & Brown, 2001; Fuchs et al., 2010; Gelman, 2008; Threlfall & Bruce, 2005), measuring and geometry (Clements & Sarama, 2011), structures (i.e., finger structures, the dice structure or the tally mark method; Andres, Di Luca, & Pesenti, 2008; Case et al., 1996; Dehaene, 1992; Rips, Bloomfield, & Asmuth, 2008), understanding the abstract number symbols (Carruthers & Worthington, 2005), knowledge of the number line (i.e., estimating the relative position of number on a linear line; Aunio, Hautamäki, & Van Luit, 2005; Ramani & Siegler, 2008), math language (i.e. ordinals and position words such as under, above, before, and after; Kleemans, Segers, & Verhoeven, 2011a; Kleemans, Segers, & Verhoeven, 2011b; Schleppegrell, 2010), and simple calculations (Carruthers & Worthington, 2004).

Next to the content of the intervention program, research on early math education revealed a number of challenges. The first challenge is an effective instruction method by the teacher adapted to the needs of the individual atypical child. This is important because differentiation at an early stage has already been considered one of the key criteria for effective classroom practice (Akos, Cockman, & Strickland, 2007; Kerry & Kerry, 1997; Levy, 2008; Smeets, 2005). Most children develop their skills on the basis of discovery, whereas others require a structured manner of learning arithmetical skills. For most children with special education needs, direct instruction is the most effective way of tutoring (Kroesbergen & Van Luit, 2003). However, this form of instruction is not integrated in all early math programs.

The second challenge focuses on the language that is involved in executing mathematical tasks. Math related language (such as the number words and math related concepts like more, less, higher, and lower) facilitates the use of numerical concepts (Gelman & Butterworth, 2005) , and research has shown some children have particular difficulties with the language of mathematics (Ginsburg, 1972; Kleemans et al., 2011a; 2011b; Schleppegrell, 2010). Such math-specific language should be explicated and integrated in a numeracy program for kindergartners (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006).

The third and last challenge relates to the manner in which children learn the meaning of the Arabic number symbols. This is often accomplished by mapping concrete quantities to the more abstract number symbols. However, for low-performing kindergartners in particular, learning to relate a tangible amount of objects to a specific written symbol is not an obvious connection. The ability to relate quantities to symbols is, nevertheless, necessary for performing more advanced mathematical tasks; according to the action theory, internalizing mental number knowledge should, therefore, happen in three levels (Pape & Tchoshanov, 2001).

To our knowledge, the effectiveness of a specific early numeracy program is never examined specifically for children with limited working memory skills, who do perform below average on an early numeracy test as well. The present study aims to examine whether remedial education on the basis of a specific early numeracy program, "The Road to Mathematics" (TRTM; Van Luit & Toll, 2013), in which the eight different aspects of early numeracy, as listed above, are covered and the main challenges in early math education are tackled, leads to improvement in the early numeracy performance of children with limited working memory skills. Thus, investigating the possibility to accelerate their development at an early stage through remedial education can provide useful insights into the opportunities of these children in the field of mathematics.

The results above lead to the following three research questions:

1. Is it possible to accelerate the early numeracy development through remedial education during kindergarten for children with limited working memory skills and low early numeracy skills? This question concerns children with limited verbal working memory skills and with early numeracy performance below average. Similar to the study of Alloway et al. (2009), children were selected on the basis of their performance on verbal working memory tasks. Although no similar interventions had been carried out for this target group, it was expected that the remedial education improved their early numeracy ability, but was not so effective for children with typical working memory skills.

2. Is it possible to accelerate the early numeracy development through remedial education during kindergarten for children with low early numeracy skills? This question concerns children with typical verbal working memory skills, but with early numeracy performance below average. Because similar interventions have been carried out for this target group (e.g., Van Luit & Schopman, 2000), it was expected that the remedial education results in an improved early numeracy ability.

3. Do children with typical working memory skills benefit more from remedial numeracy education during kindergarten than children with limited working memory skills? Because of the predictive relation between working memory and early numeracy (e.g., Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Zheng, Swanson, & Marcoulides, 2011), it was expected that children with typical working memory skills improve more due to the offered remedial education.

Method

Participants

This study is part of a large longitudinal research project that tests the effectiveness of the remedial program (TRTM) for kindergartners with below average early numeracy scores. Within this project, 26 primary schools (25 regular schools and one school for special education) in rural or urban areas in the Netherlands were involved. Participating schools were selected to reflect the national demographic profile of children concerning first, the number of children in the school, and second, the socio-economic background of the children, according to a classification system developed by the Dutch government that provides primary schools with specific finance. The whole sample included 933 children (479 boys, 51.3%) in the first year of kindergarten.[1] The mean age of these children was 4.56 year (SD = 4.07 months). Parental consent was obtained for all children who participated in this study.

At the start of the project a working memory screening and early numeracy criterion measurement were carried out. Based on these test scores, the children were divided into four different groups. This assignment procedure was carried out in three steps. First, the children were divided: either they had limited working memory skills, scoring below the 15th percentile (due to different distribution of the scores the exact cut-off percentile was 13.4, as close as possible to the 15th percentile) on verbal working memory (N = 125), or typical verbal working memory scoring above the 15th percentile on verbal working memory (N = 808). Although different cut-off scores have been used to identify limitations on learning task performance, and often the 25th percentile has been used as a criterion score (e.g., Bryant, Bryant, Gersten, Scammacca, & Chavez,

1 In the Netherlands, children begin attending kindergarten when they reach the age of four. They attend, on average, two years of kindergarten before moving to first grade in September of the year in which they turn six years old.

2008; Landerl, Bevan, & Butterworth, 2004; Passolunghi & Mammarella, 2012), for the purpose of this study, a similar cut-off score of 15th percentile, as in the study of Rouselle and Noël (2007) has been used. Second, the children were divided into children with below average early numeracy skills on the early numeracy test (N = 421) and those with above average early numeracy skills on the early numeracy test (N = 512). All children with above average early numeracy skills were excluded from this study. Third, the selected children with below average early numeracy were matched based on their early numeracy score and then randomly assigned to one of three groups. In this study, two conditions (intervention, N = 146, and control, N = 130) are included. The other 145 children are disregarded in this study, because they received another kind of intervention at the end of the second year of kindergarten. Thus, each settled condition consists of children with below average early numeracy scores and with limited or typical working memory skills, resulting in four groups: two intervention groups, one consisting of children with limited working memory skills (IL-group, N = 31) and one consisting of children with typical working memory skills (IT-group, N = 115), and two control groups, one consisting of children with limited working memory skills (CL-group, N = 43) and one consisting of children with typical working memory skills (CT-group, N = 87). In Table 8.1, information about gender, age, socio-economic status (SES), and working memory skills of the four groups is presented. SES was based on educational attainment level of both parents on a seven point scale ranging from 1 (only a few years of primary education at most) to 7 (university degree), because parental education is considered one of the most stable aspects of SES; it is typically established at an early age and tends to remain the same over time (Sirin, 2005). Note that the mean visual working memory scores of the IL- and CL-groups is significantly lower than the visual working memory of the IT- and CT-group, $t(274) = -6.63$, $p < .01$, implying the co-occurrence of low scores across different working memory systems.

Materials

Working memory

Working memory ability was measured with four computer-based tasks (Dot Matrix, Odd One out, Word Recall Forwards, and Word Recall Backwards) from the Automatized Working Memory Assessment (AWMA; Alloway, 2007) that was translated into Dutch and voice-recorded. The AWMA has a stable construct validity and good diagnostic validity for children with low working memory skills. For children aged 4.5, and 11.5 years, test-

Table 8.1 Number of children, gender, age, socio economic status, and verbal and visual working memory of the children in the four groups

		N	Gender		Age (months)		SES		Verbal WM		Visual WM	
			Boys (%)	Girls (%)	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Intervention group	Limited WM	31	14 (45.2)	17 (54.8)	53.23	4.49	3.17	2.79	4.52	1.06	8.19	3.15
	Typical WM	115	61 (53.0)	54 (47.0)	54.13	4.21	4.59	2.15	8.93	1.68	10.55	2.86
Control group	Limited WM	43	31 (72.1)	12 (27.9)	53.93	4.74	4.13	2.29	4.92	1.00	7.50	3.21
	Typical WM	87	43 (49.4)	44 (50.6)	54.01	4.45	4.72	1.93	8.97	1.88	10.59	3.31

Note. WM = Working Memory.

retest reliability of the four tasks is .83, .81, .76, and .74, respectively (Alloway, Gathercole, Kirkwood, & Elliott, 2008). Each of the four working memory tasks in the present study represents a component from the model of Alloway, Gathercole, and Pickering (2006), and all started with a short practice session. All tasks were automatically terminated when a child gave three incorrect answers within a set of items of the same length.

First, the capacity of visuospatial storage component was assessed with *Dot Matrix*. The children were presented a 4 x 4 matrix on the computer screen. A red dot shortly appeared in one of the boxes and children had to point out the correct box. The test started with a block with one dot, building up to a block with a sequence of seven dots presented across the matrix. Each block consisted of six trials that were scored as incorrect when one of the boxes was omitted, when the sequence of boxes was incorrect, or when a box was recalled wrongly. When the first four trials within a block were recalled correctly, the child proceeded to the next block. The scores could range from 0 to 28.

Second, the visuospatial processing component was measured by the *Odd One Out* task, in which children have to point out the odd shape in a row of three geometrical shapes, and remember the consecutive locations of these shapes in sets of increasing lengths. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The scores could range from 0 to 28.

Third, for the assessment of the verbal storage component, *Word Recall Forwards* was used. In this task, a recorded voice names a series of semantically unrelated words, after which the child is asked to repeat the words in the same order. The string of words becomes more and more extensive after a child has recalled several strings correctly and in the correct order. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The scores could range from 0 to 24.

Fourth, *Word Recall Backwards* was used to assess the verbal processing component. In this task, a recorded voice names a series of semantically unrelated words, after which the child is asked to repeat the words in reverse order. The string of words becomes more and more extensive after a child has recalled several strings correctly and in the correct order. The number of correctly recalled items was recorded for sets in which all items were recalled correctly. The scores could range from 0 to 24.

Confirmatory Factor Analyses (CFA) with structural equating modeling was performed on the four working memory tasks from the screening procedure. The CFA revealed a two factor model with good fit indices ($\chi^2(1) = 0.90$, $p = .34$, $CFI = 1.00$, $RMSEA = 0.00$) that is in line with the distinction made by Alloway et al. (2006), with

Table 8.2 Standardized factor loadings CFA first working memory screening procedure

		Stand. fact. loading (*SE*)	Intercept (*SE*)	Residual variances (*SE*)	Correlation (*SE*)
Visual WM	Dot Matrix	.68 (0.03)	3.06 (0.08)	.54 (0.04)	.79 (0.04)
	Odd One Out	.68 (0.03)	2.55 (0.07)	.53 (0.04)	
Verbal WM	Word Recall Forwards	.65 (0.03)	4.80 (0.12)	.58 (0.04)	
	Word Recall Backwards	.67 (0.03)	1.15 (0.04)	.56 (0.04)	

Note. WM = Working Memory. ** $p < .01$.

two latent factors – visual and verbal working memory – each latent factor having two indicators. The standardized factor loadings (Table 8.2) from the best fitting two-factor model were used to compute individual scores on visual and verbal working memory. The individual scores on the two components of working memory were used to select children. All children with verbal working memory below the 15^{th} percentile ($N = 125$) were classified qualified as having limited working memory skills.

Early numeracy

Early numeracy was measured with the *Early Numeracy Test-Revised* (ENT-R; Van Luit & Van de Rijt, 2009). The ENT-R is a 45-item standardized pencil-and-paper test for children between the ages of 4 and 7 years old. The test consists of nine parts that are indicators of early numeracy. The components can be divided into eight verbal tasks (concepts of comparison, classification, correspondence, seriation, using numerals, synchronized and shortened counting, resultative counting, and general understanding of numbers) and one non-verbal task (estimation). Each component contains five consecutive items. The total of correct answers (0–45) is the final score. There are two versions of the test, version A and version B. At time point 1 and 3 version A and at time point 2 and 4 version B was administered. The reliability coefficient of both versions of the test was good (for both versions $\alpha = .94$).

Intervention program

Intervention procedure

The program “The Road to Mathematics” (TRTM; Van Luit & Toll, 2013) aims to teach low-performing kindergartners a range of basic numerical concepts and math-related language, provide them with the meaning of numbers through structured activities, and, therefore, simplify the transition to math education in first grade. TRTM addresses a wide range of skills, and in doing so offers children a foundation upon which they can build as they enter into first grade. In line with other interventions that cover several aspects of early numeracy, eight different numeracy domains have been integrated into the program: math language, reasoning skills, counting, structures, measuring, number lines, and simple calculations. An explanation of how these eight domains are operationalized into subsidiary skills and addressed through TRTM is provided in Table 8.3.

TRTM was offered to the intervention group for a period of almost 1.5 years from halfway into the first year of kindergarten until the end of the second year of kindergarten, with in total four months of holidays in between. The program consists of 90 thirty-minute sessions with complete instructional plans and accompanying materials. Each session was divided into two or three separate tasks. Each task covered one or more skills from the eight numeracy domains as presented in Table 8.3.

Two times a week with at least one day-off in between, the 30-minute intervention sessions took place outside the classroom in small instruction groups of three to five children. At each school, one specialized female teacher was appointed, based on her expertise and kindergarten experience, to teach the remedial program to the intervention group. In two schools, the teachers became partly incapacitated due to illness, so a second teacher was added in the execution of the program sessions. The teachers received a training program of five full days in total before and after the intervention period including background information on early numeracy, role playing, video interaction feedback, and exchanging experiences.

Table 8.3 Domain overview and operationalization in skills of the early numeracy program TRTM

Domain	Skills
Math language	Number words, ordinals, position words, comparison words
Reasoning skills	Comparison, classification, correspondence, seriation
Counting	Acoustic, synchronic, skip counting, counting on, resultative counting
Structures	Fingers, tally marks, dice structure
Abstract symbols	Number symbols up to 20
Measuring	Comparison, estimations of distances, shapes
Number lines	Position of numbers, difference between numbers, relation between numbers, estimation
Simple calculations	Addition, subtraction, division

Intervention features

The program is characterized by three main features in order to meet the three challenges for early math education mentioned in the introduction section;

- The first feature of the program is the importance of instruction. All of the program tasks were presented to the children through two different instruction steps for each task (e.g., Aleven & Koedinger, 2002; Norris & Ortega, 2001): learning by doing and structure facilitation. In the first step, children are exposed to learning by doing, also referred to as 'learner-centered instruction'. The teacher has a guiding and stimulating role, and asks open-ended questions. Only when a child is not able to master a given task does the teacher switch to step two, structure facilitation. The role of the teacher expands while structuring the task, an approach referred to as 'teacher-centered instruction'. This includes direct instruction, an instructional component that increases the impact of the mathematical instruction for students with learning disabilities (Gersten et al., 2009; Kroesbergen & Van Luit, 2003). Within each task, explicit examples of instruction are clarified for both learning by doing and structure facilitation, which the teacher can use in an individualized manner to meet the instructional needs of each child.
- The second feature of the program is the importance of math related language. Within TRTM, a distinction is made between 'math language', words that are directly necessary to perform math problems and calculations (such as one, more, less or higher), and 'instruction language', language that is necessary to complete the appropriate numeracy task in an acceptable manner or to explain an adequate solution ('strategy') for a problem (such as in-a-row or one-by-one). The relevant math and instruction language for each task was highlighted in a separate frame, so that the teacher could use the specific to-be-learned terms extensively in an effort to elicit the same language from the children. The teacher provides the math and instruction language explicitly during each task, because research has shown a significant relation between the amount of teachers' math-related talk and the growth of preschoolers' conventional mathematical knowledge over the school years (Klibanoff et al., 2006).
- The third feature, the importance of internalization, is based on a theory which states that internalizing mental operation occurs at three discrete levels (Pape & Tchoshanov, 2001). Three levels of material use are, therefore, offered as part of TRTM: concrete materials, which are tangible objects such as blocks, pawns, and fingers; semi-concrete or pictorial representations, such as tallies or the dice

structure described above; and, abstract symbols, which facilitate the transition from concrete quantities, or 'material operations', to a mental meaning of number symbols, or 'mental acts'. The program initially focuses primarily on offering concrete materials (McNeil & Uttal, 2009). Semi-concrete materials are offered later in the program, with the goal of eventually reaching the third level, the internalization of abstract numerical symbols. The use of tally-marks, based on the program of Van Luit and Schopman (2000), as well as the more traditional dice-structure, are materials which function at the semi-concrete level. The structures symbolize the reality but are more abstract than reality, and, therefore, function as a semi-concrete in-between stage which attempts to bridge the gap between present knowledge and formal numeracy (Bruner, 1966). Using these structures as perceptual gestalt – a configuration of elements so unified as a whole that its properties cannot be derived from a simple summation of its parts – the gap between situated knowledge (four concrete objects, such as apples) and formal mathematics (the abstract number symbol 4) can be bridged. The tally-mark use – in which each of the five tallies are enclosed with an ellipse instead of by pulling the first four tallies through with a fifth, long, diagonal tally – helps children understand that the number '5' represents five objects and that numbers are based on patterns (5, 10, 15, etc.). The number '5' was chosen in part because patterns of five suit the decimal system, and correspond with the natural finger counting strategy of children. This structure will, moreover, stimulate shortened counting when a child discovers that an ellipse always includes five tallies. The tally-mark method is added next to the more traditional dice-structure, as some children found the dice-structure ambiguous and unstructured (Van Luit & Schopman, 2000).

Implementation fidelity

Implementation fidelity is controlled in three manners: (1) after each session the teacher filled out a standardized digital evaluation checklist for each group including standardized questions about the execution and the behavior of the children; (2) once fortnightly, each fourth session was video-taped. For each teacher, 22 video recordings are available. All video recordings were viewed and globally checked on nine implementation criteria (Justice, Mashburn, Hamre, & Pianta, 2008); (3) the implementation was checked by a visit to each school and by monitoring the process through phone calls every two months.

Procedure

The working memory screening procedure and the early numeracy criterion measurement happened halfway into the first year of kindergarten (January 2011). The selected children were divided into four groups based on their working memory and their early numeracy score. The children assigned to the intervention groups received remedial education according to the program twice a week in 30-minute sessions, and did not attend the regular math lessons in the classroom. The children in the control groups were systematically offered (i.e. one hour a week as well) the regular classroom curriculum following a standardized math method. Although the intervention period covered 16 months, added together there were four months of holidays in this period. Therefore, the absolute intervention period (12 months) was used in the subsequent analyses. Early numeracy ability was measured three times again with a standardized early numeracy test, after three, nine, and twelve months (posttest). These measurement points were, again, absolute points controlled for the holiday periods in between. All tests were administered by trained graduate students, who hold a Master's Degree in Special Education or Psychology. Each assistant received three hours of training regarding the instruments and then administered a trial test session with a child, after which they received feedback. The children were tested individually in a quiet area of the school for two (screening measurements) or one (early numeracy measurements) 20- to 30-minute session. All tasks were obtained in a fixed sequence.

Statistical analyses

First, the early numeracy test scores on the four time points of the four groups are presented. Preliminary analyses revealed no group interaction effects involving age or gender. Therefore, these variables were excluded as covariates in subsequent analyses. The deletions, in turn, functioned to make the model more parsimonious and easier to interpret.

Second, a repeated measures ANCOVA was conducted to test whether the mean gains between the four measurement points for early numeracy differed between the four groups: whether the development of the IL-group differed from the CL-group (first research question), whether the development of the IT-group differed from the CT-group (second research question), and whether the development of the IL-group differed from the IT-group (third research question). Mauchly's test of sphericity was used to test the assumption of sphericity. Because this assumption was violated, the Greenhouse-Geisser correction was conducted. Post hoc analyses with a Bonferroni adjustment were carried out correcting for an experiment-wise error rate. In addition to *p*-values, effect sizes are reported using the partial eta-squared (η^2). The critical values for this measure are 0.01 for a small effect, 0.06 for a medium effect, and 0.14 for a large effect (Cohen, 1988).

Although children were randomly assigned to the intervention and control groups, pretest early numeracy scores served as a covariate, next to the covariate SES, in order to control for pretest differences between the groups with limited and the groups with typical working memory. The covariates served the dual purpose of (a) minimizing any potential confounding that might be attributable to prior mathematics knowledge between the four groups and (b) reducing unexplained variance and, thereby, increasing the power of the analyses to detect treatment effects (Field, 2005; Maxwell & Delaney, 2004).

Results

Descriptive statistics

Table 8.4 provides mean raw scores and standard deviations for early numeracy for all four groups at the four measurement points. In total 57 scores (5.2%) were missing because of moving (N = 20) or due to illness, long absence or transfer to another class (N = 9).

Figure 8.1 provides a visual representation of the data from Table 8.4, and it reveals that both intervention groups showed larger growth on early numeracy scores than children in the control groups. Over the four EN test points, the IL-children went from 16.8% to 58.8% correct, whereas the CL-children went from 16.1% to 41.6% correct, and the IT-children went from 22.6% to 65.7% correct, whereas the CT-children went from 22.2% to 50.3% correct.

Inferential statistics

The repeated measures ANCOVA showed a large main effect of time in the expected direction, $F(2.71, 534.01) = 97.84$, $p < .01$, $\eta^2 = .33$. However, the significant development was not found between the third and fourth measurement, $F(1, 197) = 1.04$, $p = .31$, $\eta^2 = .01$. Furthermore, a large main effect of group, in favor of the two intervention groups (the IL-group and the IT-group), was found, $F(3, 197) = 32.01$, $p < .01$, $\eta^2 = .33$. From Table 8.5, it can be concluded that children with limited working memory skills and children

Table 8.4 Early numeracy scores of the four groups on four measurement points

		Pretest			After three months			After nine months			After twelve months		
		N	EN score		*N*	EN score		*N*	EN score		*N*	EN score	
			M	*SD*		*M*	*SD*		*M*	*SD*		*M*	*SD*
Intervention group	Limited WM	31	7.55	3.75	31	10.97	4.61	29	25.31	7.97	29	26.48	7.07
	Typical WM	115	10.18	4.42	114	15.25	4.88	110	27.91	6.24	110	29.55	4.63
Control group	Limited WM	43	7.26	3.44	39	10.79	3.87	35	17.14	6.26	34	18.71	6.63
	Typical WM	87	9.97	4.25	84	13.86	4.82	78	21.60	5.58	78	22.65	5.85

Note. WM = Working Memory, EN = Early Numeracy.

with typical working memory skills in the control condition obtained lower scores than children with limited working memory skills and children with typical working memory skills in the intervention condition. A significant interaction effect was revealed, $F(8.13, 534.01) = 16.76$, $p < .01$, $\eta^2 = .20$. The IL-group and IT-group developed faster than the CL-group and CT-group, except between the third and the fourth measurements, $F(3, 197) = 0.52$, $p = .67$, $\eta^2 = .01$. Moreover, no difference in development was found between the IL-group and the IT-group.

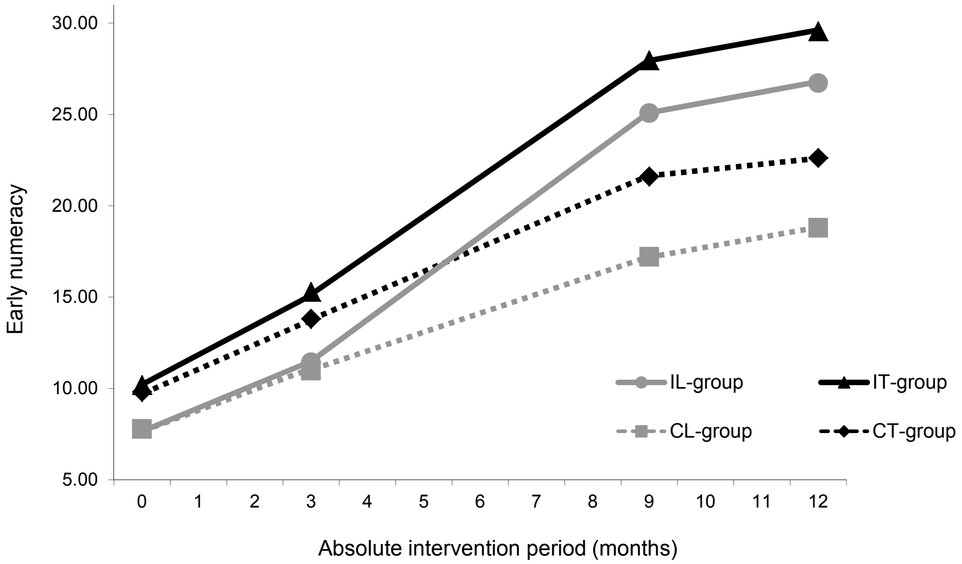

Figure 8.1 Early numeracy growth of the four groups on the four measurement points.

Table 8.5 Group comparisons on mean early numeracy scores over four measurement points

Group (I)	Group (J)	MD (I-J)	Std. error
IL-group	IT-group	-1.15	0.70
	CL-group	4.06**	0.81
	CT-group	2.02*	0.74
IT-group	CL-group	5.21**	0.60
	CT-group	3.16**	0.48
CL-group	CT-group	-2.04*	0.64

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

Discussion and conclusion

The primary purpose of the current study was to examine whether remedial education on the basis of a specific early numeracy program during kindergarten leads to improvement in the early numeracy performance of children with limited working memory skills. Children with limited working memory skills, who were identified via population screening on the basis of scores below the 15th percentile on two verbal working memory tasks, scoring below average on a standardized early numeracy test, were the target group for the intervention applied in this study. Intervention at an early stage may give children low-performing in math the opportunity to catch up with their typically-achieving peers, thereby allowing them to obtain sufficient basic mathematical knowledge by the start of first grade. This in turn might allow these children to take greater advantage of the education offered during primary school, in terms of both curriculum and instruction. In order to compare these children to children with typical working memory skills, it was also examined whether the second target group benefits from remedial early numeracy intervention before starting conventional math education in grade one. Doing so also allowed the authors to investigate whether the results of the intervention scheme were consistent across the two target groups.

The results indicated that application of the early numeracy program did indeed influence the development of early numeracy of the participating children in the two intervention groups (first and second research question). During and after the intervention period of 1.5 years the two intervention groups showed a greater progress on the early numeracy test that was administered on four different time points. These results are consistent with similar research by, for example, Krajewski et al. (2008) on typically developing kindergartners, and research by Dyson et al. (2011) on at-risk children from low economic status families, and research by Van Luit and Schopman (2000) focusing on children with low early numeracy ability. However, to our knowledge this is the first study that shows the possibility to support early numeracy skills specifically for children with problems in working memory.

With respect to the third research question, it can be concluded that both target groups benefit similarly from the offered intervention indicating that remedial curriculum is necessary and helpful for children with typical working memory skills as well as for children with limited working memory skills, despite the relation between working memory and early numeracy development (e.g., Meyer et al., 2010; Zheng et al., 2011). However, the mean early numeracy level of the children with typical working memory remains higher than the level of children with limited working memory skills.

Nevertheless, the finding means that the children from both intervention groups were better prepared for math instruction in first grade than their control peers with similar working memory ability.

Non-significant improvement applies to all four groups during the last three months of the study. Therefore, the reason why the difference in progression of the intervention groups versus the control groups was not found between the third and fourth time point can likely be ascribed to the relative short amount of time between these two measurements.

In the current study, only the effect on early numeracy learning was taken into account. It would be interesting to investigate whether the remedial numeracy education also leads to improvement in other domains such as planning or attention span, as well as more learning-related skills such as language or reading comprehension. For this reason, future studies should take other measurements into account to see if improvement is broader than the specifically trained numeracy skills. Moreover, future studies should include follow-up measurements in at least first grade to investigate whether early numeracy intervention during kindergarten leads to higher mathematical attainment in the long run.

While the current study controlled for the time the different groups received math instruction, a limitation is the difference in group size between the intervention and control groups. In cases where the intervention sessions took place in groups with a maximum of five children, the classroom math lessons were offered to groups varying from three to fifteen kindergartners. Within the current study it was examined whether remedial education is an effective way to support early numeracy development, and it turned out to be so. However, it is possible that the early numeracy gains seen in the intervention groups were (also) the result of special treatment or small-group-instruction more generally, rather than the content of the remedial program. Nevertheless, the results imply that for these target children it is important to offer a remedial curriculum in small groups. In future studies, however, it is recommended that researchers include a regular-curriculum-condition, carried out in small groups, to compare with the number sense condition. In the ideal design, this condition would exist alongside a care-as-usual control condition, as was done in the current study.

Another limitation concerns the analytical methods used in the current study. It would be interesting to consider the nesting of the data (i.e., time points nested into children, children nested into classes, and classes nested into schools) and then to analyze the intervention data in multilevel models (Hox, 2010). Unfortunately, to do this would require a given number of children in each class and each school, and this was not possible in the current design, because the four groups are derived from a large sample of 27 schools. In case of a multilevel design, the effect of teacher quality on the effectiveness of the program can be taken into account, because previous research by, for example, Clements, Sarama, Spitler, Lange, and Wolfe (2011), has shown that the quality of teaching mediates treatment effect in early mathematics learning by young children.

The current study also revealed another interesting finding. Consistent with research by Alloway et al. (2009), the low levels of performance of the sample selected on the basis of poor verbal working memory also extend to their visual working memory. This supports the notion that working memory problems are pervasive, affecting both verbal and visual systems in children identified as having limited working memory skills, and working memory capacity is best captured by a domain-general component (e.g., Baddeley, 2000).

To summarize, remedial education during kindergarten led to better performance of early numeracy skills for both kindergartners with limited working memory skills and below average early numeracy as well as for children with typical working memory and below average early numeracy. Therefore, intervention can help kindergartners with below average early numeracy to develop a foundation for mathematical knowledge. This study does confirm the continuing need to assist children through prevention programs with a focus on early numeracy in an educational setting.

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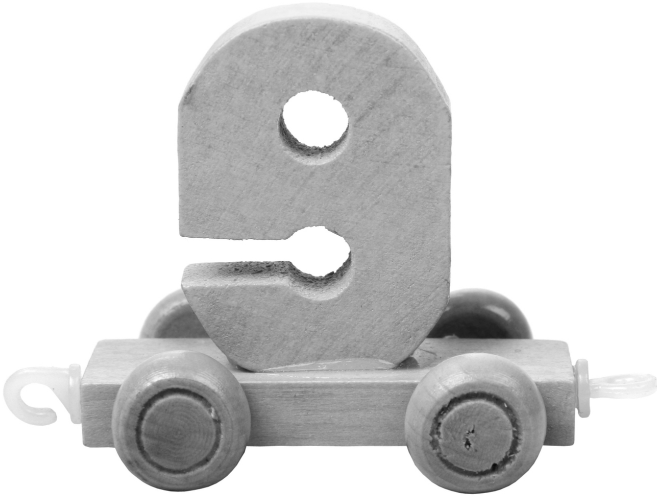

Summary and general discussion

Over the past two decades, an increasing number of studies have demonstrated the importance of early numeracy development as a prerequisite for formal mathematics education starting in the first grade (e.g., Jordan, Glutting, & Ramineni, 2010). As mentioned in the introduction (Chapter 1), the research in this dissertation focuses on children whose early numeracy abilities do not develop spontaneously while following the regular kindergarten curriculum, and who therefore tend to remain behind throughout their schooling (e.g. Duncan et al., 2007). The work of this dissertation is intended as a contribution to the growing body of knowledge about the importance of early numeracy in the first years in the school career of children, especially in those who are at risk of developing math learning difficulties. In order to do so, three main aims were addressed: examining low early numeracy as important precursor of disturbed mathematical development, identifying several predictors in delayed early numeracy learning and testing the effect of remedial intervention for children lagging behind in early numeracy. In this final chapter, the conclusions regarding those aims will be briefly summarized and will be discussed in the light of other studies within the subject of early numeracy. These conclusions are structured following the five arrows from the figure as presented in Chapter 1 (see Figure 9.1). At the end of this chapter, directions for future research along with practical implications of the present research will be provided.

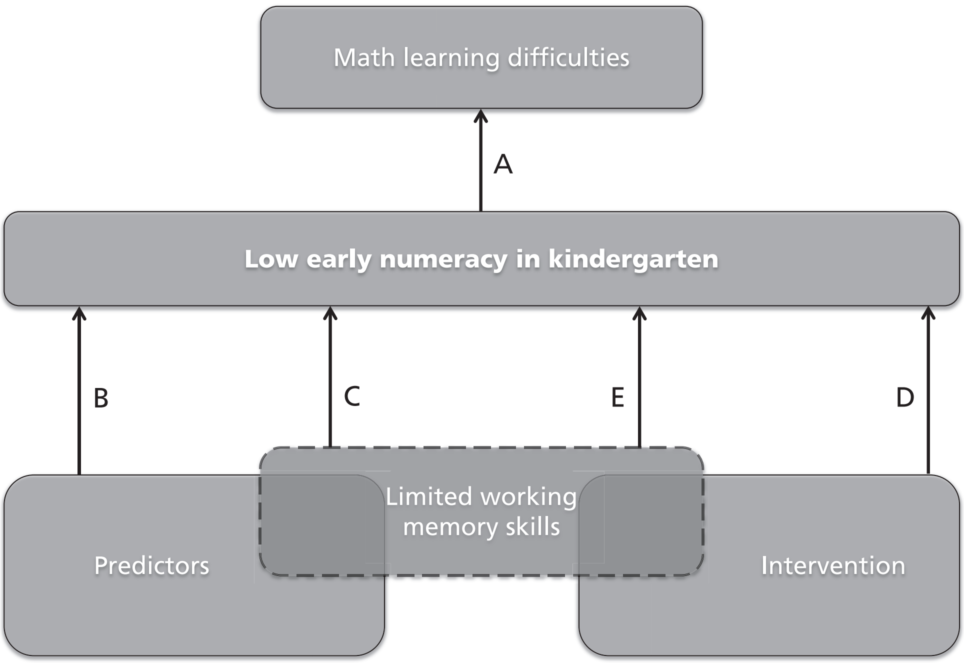

Figure 9.1 Five arrow-structure of this concluding chapter.

Arrow A: The predictive value of low early numeracy

From previous research it is known that wide individual differences in early numeracy are already present in kindergarten (e.g., Aunio & Niemivirta, 2010). An increasing number of studies have investigated early numeracy skills as a prerequisite of mathematical proficiency in primary school (e.g., Jordan, Kaplan, Locuniak, & Ramineni, 2007). They emphasise the necessity of having a thorough command of early numeracy skills, because developing mathematical skills builds on previously learned early numeracy skills. Unfortunately, less studies have focused specifically on children with low achievement levels (e.g., Morgan, Farkas, & Wu, 2009), or have compared early numeracy directly with other predictors such as executive functions or in particular working memory (Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009). In the study reported in Chapter 2, the impact of early numeracy diversity and executive functions as precursors to math learning disabilities was explored by predicting group classifications. These classifications were based on – persistent – math achievement throughout first and second grades. Discriminant analyses revealed that early numeracy – in Chapter 2 referred to as preparatory mathematical abilities – and working memory, or the related concept of updating, but not shifting and inhibition, could predict group membership most effectively. Almost all children (95.3%) with persistent mathematical difficulties were identified as having, or being at risk of having, problems in mathematical performance. Thus, the results confirm the importance of early numeracy skills in identifying which children are at risk of experiencing math learning difficulties at the beginning of primary school (e.g., Stock, Desoete, & Roeyers, 2010), but also correspond with previous studies in which a relationship was established between working memory and mathematical difficulties (e.g., Bull, Espy, & Wiebe, 2008). In these studies, it is assumed that working memory is necessary for learning basic arithmetic in first and second grade, because information must be stored and manipulated continuously during mathematical activities (Vukovic & Siegel, 2010).

The results from Chapter 2 clearly support the assumption that early numeracy is an integral part of the developmental trajectory towards mathematics and therefore this study set the stage for the other two aims in this dissertation; examining predictors of low early numeracy and explore the intervention possibilities for children at-risk for developing mathematical learning difficulties.

Arrow B: Predictors of low early numeracy

In this dissertation, the role of predictors in the development of low early numeracy skills has been examined. Investigating which early predictors, or underlying factors, contribute to inadequate early numeracy skills can help us unravel the development of early numeracy. Furthermore, the discovered predictors can be addressed as key components in remedial programs preventing at-risk children for not falling further behind. In this dissertation, the distinction between domain-general predictors – working memory and (specific math) language – and domain-specific predictors – in particular comparison skills – has been used (Passolunghi & Lanfranchi, 2012). Each of these concepts was measured at different time points throughout kindergarten. Early numeracy was assessed at four time points between halfway through the first year and at the end of the second year of kindergarten, because during this period, the children involved in the studies were at a crucial age for developing increasingly early numeracy skills and its related concepts. The first early numeracy measurement was taken shortly after children were introduced to kindergarten, at age four in the Dutch education system. They had little or no experience of explicit instruction in early numeracy activities as offered in kindergarten and were therefore expected to develop these abilities in the years from kindergarten to first grade. Applying a longitudinal design allowed an examination of the development of early numeracy skills in children at-risk of developing math learning difficulties.

Language

The involvement of language in low early numeracy development throughout kindergarten was examined, mainly because adequate language acquisition has been argued to be a prerequisite for learning early numeracy (Dehaene, Piazza, Pinel, & Cohen, 2003; Duncan et al., 2007). One part of language that has been hypothesized to be especially important for the development of early mathematical ability is math related language (Greenes, Ginsburg, & Balfanz, 2004; Pruden, Levine, & Huttenlocher, 2011). Therefore, specific math language was included as predictor of weak early numeracy development in the study reported in Chapter 3. Remarkably, the results showed the predictive value of specific math language as most important, even over and above the predictive value of working memory and comparison skills, which are factors that are investigated far more frequently in relation to early numeracy. This finding has led to a more detailed examination of the interrelations between general language, specifically math language and early numeracy within kindergartners with low early numeracy. In this study, as reported in Chapter 4, the interrelations were explicitly tested using a design in which general language skills and early numeracy skills were assessed at four different measurement occasions in the first and second year of kindergarten, and specific math language was assessed in the second year. Analyses using multivariate growth models yielded two main findings. First, the results showed the existence of a mutual relationship between language development and early numeracy development in kindergartners with (very) low early numeracy. In other words, initial status of both skills, as well as growth rates, are interrelated and influence each other reciprocally, and moreover, the initial status of general language affects the early numeracy development throughout kindergarten. Thus, the data in this dissertation confirms the idea that the development of early numeracy is highly dependent on language (e.g., Hooper, Roberts, Sideris, Burchinal, & Zeisel, 2010; Romano, Babchishin, Pagani, & Kohen, 2010). A second finding elaborates on the first finding by revealing specific math language as an intervening – or mediating – variable within the developmental relation between general oral language and early numeracy, and therefore states the importance of specific math language in early numeracy. This result provides evidence for the suggestion that specific language terms facilitate the use of numerical concepts during numerical performances, as proposed in previous research emphasizing the role of (specific) language in early numeracy development (Gelman & Butterworth, 2005; Halberda, Taing, & Lidz, 2008; Sarnecka & Gelman, 2004).

An explanation for this result can be found in the linguistic aspects of early numeracy. At least in our Western culture, learning particular early numeracy skills is primarily a verbal matter. For example, learning the verbal counting sequence and naming the number symbols are verbal skills in which linguistics are actively involved. Also, knowledge about the position of numbers on a number line is associated with linguistic concepts (the four comes *after* the three). Lansdell (1999) proposes the introduction of this specific math terminology as an important part of the teaching of early mathematical concepts. Therefore, applying early numeracy skills when a caregiver or teacher is present and providing verbally offered instruction requires a certain language level of a child. If children experience particular difficulties in the language of mathematics (Ginsburg, 1972; Schleppegrell, 2010) this automatically harms their opportunities in learning early numeracy skills.

Working memory

Where Chapter 2 already revealed working memory as a predictor of math learning difficulties in the first and second grade, in other chapters of this dissertation working memory is associated with prerequisites of math achievement, or in other words early numeracy. As is in basic arithmetical procedures in children aged 6 to 8 years (Mabbott & Bisanz, 2008), and in executing early numeracy tasks, a child aged 4 to 6 years constantly needs to revise their stored information (Espy et al., 2004). In other words, young children need to invoke their working memory, for example, when they recite the counting sequence, produce information concerning number symbols, or compare sets of quantities.

In the second study of this dissertation, as we reported in Chapter 3, working memory was used to predict early numeracy development in weak-performing children. A cut-off score of the 15th percentile was deliberately chosen in order to select only those children with severe arrears in early numeracy (Desoete, Roeyers, & De Clercq, 2004). Following the distinction between visual and verbal working memory made by Alloway, Gathercole, and Pickering (2006), in turn derived from the working memory model proposed by Baddeley and Hitch (1974), the two working memory components – visual and verbal – were included separately in the analyses.

From the multilevel latent variable growth model, in which the nested structure of the data was taken into account, it can be concluded that working memory indeed plays an important role in early numeracy skills. This is congruent with previous research (e.g., Kyttälä, Aunio, & Hautamäki, 2010) and confirms the hypothesis that working memory contributes to early numeracy achievement (Meyer, Salimpoor, Wo, Geary, & Menon, 2010; Zheng, Swanson, & Marcoulides, 2011). More specifically, visual working memory predicts variance on the general level, whereas verbal working memory has a meaningful influence on the development – the growth rate – of early numeracy. So, concerning their general early numeracy level in kindergarten, children appeal to their visual working memory when performing early numeracy, whereas concerning their developmental growth during kindergarten, having well-functioning verbal working memory skills is beneficial. This confirms the idea discussed by Raghubar, Barnes, and Hecht (2010), suggesting that visual working memory is more specific to early mathematical learning, and that verbal working memory is more generic in terms of supporting learning (i.e., development). In other words, the studies suggest that visual working memory is used for learning new early numeracy skills (when entering kindergarten), whereas verbal working memory comes into play after an early numerical skill has been learned (Raghubar et al., 2010). However, the results do not match all available knowledge on this subject. One assumption, stating that the effect of visual and verbal working memory on (early) mathematical proficiency is related to children's age (Rasmussen & Bisanz, 2005), was been supported by the results in this dissertation.

The findings of this dissertation indicate that verbal working memory is most important in the development of early numeracy skills in at-risk children aged 4 to 6, whereas in previous studies visual working memory had been repeatedly related to math performance within this age range (e.g., Holmes & Adams, 2006). This may be attributable to the verbal nature of the early numeracy test used or to the fact that learning early numeracy in an educational setting is mainly a verbal matter (as discussed above), although this contrast could presumably be better ascribed to the fact that the focus was specifically on children having problems with internalizing early numeracy skills and concepts. Other studies have shown limitations in verbal working memory as being an important predictor for math outcomes in this particular interest group of at-risk children (e.g., Swanson & Jerman, 2006). Several explanations for this phenomenon have been proposed, such as the idea that core deficits in semantic memory underlie the difficulties, but until now, no significant explanation has been proven correctly.

Another explanation of the significant but unexpected contribution of verbal rather than visual working memory can be found in the conception that working memory capacity is best captured by a domain-general component (e.g., Baddeley, 2000). This explanation is supported by an interesting finding revealed in Chapter 8. The results in this chapter, reporting a study on intervention possibilities for children with limited working memory skills, showed that low levels of performance on verbal working memory often also extend to restrictions in their visual working memory. Consistent with research by Alloway, Gathercole, Kirkwood, and Elliott (2009), this conclusion supports the notion that working memory problems are pervasive, affecting both verbal and visual systems in children identified as having limited working memory skills.

Comparison skills

In this dissertation, examining the contribution of domain-specific predictors in low early numeracy at the kindergarten level was concentrated on comparison skills and more specifically on the discussion about whether mastering non-symbolic or symbolic comparison skills were more important conditions for learning early numeracy skills. From research into typical developing children, evidence can be found illuminating the importance of non-symbolic skills (e.g., Gilmore, McCarthy, & Spelke, 2010), but also for the contribution of symbolic skills (e.g., Rousselle & Noël, 2007). In Chapter 3, an attempt has been made to provide insight in this issue when it comes to children having difficulties in learning early numeracy skills. In the analyses, comparison skills were modeled as predictors of weak early numeracy alongside working memory and specific math language, as discussed before. Early numeracy in at-risk children was measured on four different occasions throughout kindergarten. The results proved non-symbolic comparison skills to be important for the intercept whereas symbolic comparison skills influenced the development. Instead of providing evidence for the importance for either non-symbolic or symbolic skills, the results showed non-symbolic skills as an important starting requirement and symbolic skills as a predictor for development. Although no clear conclusion can be drawn, the results seem to indicate that symbolic skills come into play when more complex numeracy abilities are elicited. Therefore, based on the results of this dissertation, it could be suggested that being capable of comparing the value of symbolic information - i.e., comparing the value of Arabic number symbols – is more important for children lagging behind in early numeracy. It must be noted, however, that the symbolic comparison task used in this dissertation demanded, besides knowledge of the number symbols per se, the higher-order ability to connect the meaning of the symbols to their corresponding quantity; also referred to as mapping skills (e.g., Kolkman, Kroesbergen, & Leseman, 2013). Symbolic comparison skills thus might help children to reach milestones within the process of learning early numeracy skills as preparations of basic mathematical competence. This emphasizes the results of previous studies in that non-symbolic skills seemed to play a subordinate role in learning math in contrast to the much more important role of symbolic skills (e.g., Holloway & Ansari, 2009; LeFevre et al., 2010).

Regarding the role of early numeracy predictors in children staying behind in kindergarten, it can be concluded that all predictors examined in this dissertation are important in learning early numeracy skills, with specific math language having the greatest impact compared to working memory and comparison skills. Together these predictors explained a high amount of variance in the early numeracy development, although up to forty percent of the variance in development of at-risk children remained unexplained. Nevertheless, now that the predictors were included in one design focusing on children with weak early numeracy, they were are uncovered as reliable and promising targets to include in future intervention studies for those at-risk children. In turn, more information about the processes involved in the development of this specific target group can be provided by investigating the possibility of accelerating early numeracy skills, which is the third aim of this dissertation.

Arrow C: Early numeracy in children with limited working memory skills

The above findings concerning the role of working memory in low early numeracy suggest that a certain working memory capacity is necessary for executing early numeracy tasks, and therefore it can be assumed that children with limited working memory skills are at a disadvantage compared to their peers with typical working memory skills. This seems also the case when looking into the available literature on the consequences of having limited working memory resources (e.g., Alloway et al., 2009). Therefore in two other studies, both reported in Chapter 7, the difficulties which children with low early numeracy skills as well as limited working memory experience in performing early numeracy tasks, were explored. In each study, kindergartners with limited working memory skills were selected from a large screening sample and were then classified into three groups based on the specificity of the restrictions in their working memory skills. Consequently it was possible to compare children with problems in verbal working memory, children with problems in visual working memory, and children with more general problems in both verbal and visual working memory. In the next step in both studies, a control group was added to the classification, representing children who perform typically on working memory tasks.

From the first study it became clear that children with limited working memory skills often experience difficulties in general early numeracy, and also the development of a number of specific early numeracy skills is slower than the development of children with typical working memory skills. The second study was carried out to focus in more detail on the numerical aspects of early numeracy. From this study, it can be concluded that children with specific limitations in one working memory system do not experience problems in specific numerical skills (i.e. verbal working memory limitations do not lead to deficits in mastering the counting sequence or other verbal number skills, and visual working memory limitations do not lead to deficits in mastering visual number symbols). Children with limitations in both working memory systems, however, do experience more problems in the different numerical tasks.

Thus, the hypothesis that children with limited working memory skills are at an advanced risk of developing serious mathematical learning difficulties during primary school (Schuchardt, Maehler, & Hasselhorn, 2008) was proven to be correct within the two studies presented in Chapter 7.

Arrow D: Early numeracy support

Attention has increasingly been paid to stimulating early numeracy in children with low early numeracy skills (e.g., Bryant et al., 2011; Van Luit & Schopman, 2000). These studies use the practical importance of studying the possibility of stimulating early numeracy as a starting point. They state it is desirable to investigate the effectiveness of preventive interventions for kindergartners and school beginners with inadequate early numeracy skills who have not yet begun to fail in school (Dowker, 2005), because it is expected that effective early math interventions would decrease the number of children who are retained in first grade (Moser, West, & Hughes, 2012). Recently conducted studies have assessed intervention efficacy for at-risk kindergartners. In most of these studies, children from low-economic status families, classified as being at-risk, were target of the intervention (e.g., Dyson, Jordan, & Glutting, 2013; Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012). However, in a limited number of studies, children were detected as being at-risk based on their early numeracy abilities (e.g., Aunio, Hautamäki, & Van Luit, 2005; Kamii, Rummelsburg, & Kari, 2005), as was done in this dissertation.

Effects of intervention

For the third aim of this dissertation, a specific remedial intervention for early numeracy was developed and revised in collaboration with a large number of educational professionals, in order to investigate the usability of remedial early numeracy programs in kindergarten. The most useful program in this area is called *The road to mathematics* (Van Luit & Toll, 2013) and is based on several theoretical and empirical findings which have been found to be effective for kindergarten education. More information about the features, domains and skills offered can be found in the chapters 5, 6, and 8 in this dissertation. In these three studies it was tested whether *The road to mathematics* could effectively accelerate the development of early numeracy throughout kindergarten. Although the three studies use different designs and analytic methods, overall it can be concluded that *The road to mathematics* is an effective program for remedial early numeracy support in kindergarten.

The first study – Chapter 5 – functioned as a pilot study and therefore used an abbreviated version of the program. The performance of the intervention for children, which involved eight weeks of training, was compared with that of matched control children and of typically achieving children. Although all three groups made gains in early numeracy over the course of that study, the intervention children realized larger gains than the control children and, when pretest level was held constant, than the typically-achieving children. The finding that the early numeracy of the intervention children scoring below average increased via a relatively brief intervention regimen was encouraging, especially given that kindergarten early numeracy predicts a high success rate on a mathematics test in second grade (Locuniak & Jordan, 2008) and in third grade (Jordan et al., 2010). However, it should be mentioned that the effects on the children within the lowest range in early numeracy (lower than the 25^{th} percentile) did not reach the designated threshold of statistical significance. Based on these results, the conclusion can be drawn that the intervention regimen was effective only for those children showing acceptable levels of early numeracy.

Thus, in this study no significant effects were found for those children having very low early numeracy. Since very low early numeracy in kindergarten can predict the future presence of a math-related learning disability in third grade (Mazzocco & Thompson, 2005), the finding that intervention was effective only for children with scores approaching the average, raised questions about the design of the pilot study. Considerations for the main study (as described in Chapter 6) were threefold. First, intervention should be offered over a longer time period and one should experiment with the length of the intervention period (Kroesbergen & Van Luit, 2003). This enables a design that can provide information about whether longer or shorter intervention duration produces the best results for children performing below average. Second, the intervention sessions should be offered by kindergarten teachers instead of trained supervisors. In this way, the question of whether the intervention is effective and applicable within the existing learning environment of the school could be explored (Lodico, Spaulding, & Voegtle, 2010). Third, follow-up measurements should be included to examine whether the remedial program led to a deeper understanding of numerical relations and whether the intervention children realized greater benefits from math education in first grade as a result of the conceptual number knowledge obtained and developed through the intervention regimen (Dyson et al., 2013).

The above list of considerations has led to adaptations in the design of the main study, as described in Chapter 6. In that study, the effects of remedial early numeracy support of two different duration lengths was tested. To this end, two versions of *The road to mathematics* were designed and four different conditions were distinguished; a complete intervention condition receiving 1.5 school years of intervention (using the complete version of the program), a short intervention condition receiving 0.5 school years of intervention (using the short version of the program), a matched control condition following the regular curriculum, and a typically-achieving condition following the same regular curriculum as the matched control condition. Overall, it can be concluded that those children who had participated in the program, offered by teachers from their own school, performed better than the children who had followed the regular curriculum, which is congruent with prior intervention studies (Baroody, Eiland, & Thompson, 2009; Dyson et al., 2013; Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005). Direct effects on early numeracy for both versions of the program were found at post-test (end of kindergarten) and at follow-up test (halfway first grade). The strong effects of the follow-up test for both intervention conditions suggest that children internalized what they had learned. Furthermore, many of the interventions involved children being able to transfer the learned knowledge into more complex abilities which were not present in the activities of the program. Transfer effects at post-test were found on simple arithmetic skills, only for the complete version, and complex mathematical computations for both versions. In short, children receiving structural remedial support during kindergarten turned out to be better in mathematical proficiency than their classmates attending the regular curriculum. Children with a thorough command of the prerequisite early numeracy skills after the intervention were better able to learn the subsequent mathematical skills. This finding suggests that children either transferred the knowledge they gained during the intervention to less familiar, more conventional skills or were better prepared for, and therefore benefited more from, the mathematical activities offered in first grade. While children with problems in mathematics often fail to apply acquired skills in new situations (Van Luit & Naglieri, 1999; Van Luit & Schopman, 2000), the transfer effects found in this dissertation do not stand alone (e.g., Fuchs, Fuchs, Hamlett, & Appleton, 2002; Rittle-Johnson, 2006). Direct experience of the extension and modification of strategies, in combination with self-explanation and direct instruction (Rittle-Johnson, 2006) embedded in the used program might be the reason for the unassisted generalization of the skills learned by the children included in the main study.

Even though the typically-achieving children gained the highest early numeracy scores on both post-test and follow-up, when initial early numeracy achievement was held constant, the children in the complete intervention condition, but not the short intervention children, showed more improvement at the post-test stage than the typically-achieving children. Also in complex mathematics, the children that received 1.5 school years of support scored relatively better than their typically-achieving peers, which implies that it may be possible for the at-risk children to catch up with their typically-achieving peers before they start formal math education at six years old in first grade.

Effects for low achieving children

To gain additional insights into how beneficial intervention is for low achieving children, intervention effects were compared for poor achieving children (scoring below the 25th percentile) and children scoring below average (between the 25th and 50th percentile) in Chapters 5 and 6. In the pilot study – Chapter 5 – the effects did, as mentioned before, not reach the designated threshold of statistical significance for the children within the lowest range in early numeracy. Based on the main study – Chapter 6 –, however, it can be concluded remedial education during several months leads to positive outcomes for both subgroups. Although the results were not very ambiguous, the effect sizes were slightly stronger for the poor achievement children, especially when they received 1.5 year of remedial education. This difference can probably be ascribed to the lower starting level of these children providing them more developmental opportunities. Comparing the results of Chapter 5 and Chapter 6, the findings emphasize the importance of structural long-lasting remedial education for poor achievement children being mostly at risk, and thus not support that lasts for eight weeks only. Remedial education within a timeframe of several weeks seems to be effective only for those children showing acceptable levels of early numeracy.

Arrow E: Early numeracy support for children with limited working memory skills

Additional analyses were carried out to test whether intervention is also effective for at-risk kindergartners with limited working memory skills. In the study described in Chapter 8 it was examined whether remedial education through *The road to mathematics* leads to similar improvement in the early numeracy performance of children with limited working memory skills as the improvement of children with typical working memory skills. The results indicated that both target groups benefited similarly from the intervention offered, indicating that remedial curriculum is necessary and helpful for children with typical working memory skills as well as for children with limited working memory skills. Although the mean early numeracy level of the children with typical working memory remained higher than the level of children with limited working memory skills, the analyses demonstrated that *The road to mathematics* was also effective for this target group.

Several theoretical and substantive features of the program might be responsible for the effectiveness described in Chapters 5, 6 and 8. This could involve a) the wide range of skills, classified into ten domains, that were offered within the program; b) the extensive attention that was paid to math related language; c) the possibility of adapting the teacher instruction to the individual child; d) the special interest that was placed on the internalization of the symbolic number symbols by the use of tally marks as perceptual gestalts; e) the frequency – two times a week – or the length – 1.5 or 0.5 years – of the intervention; or f) the great variety of instructional materials, input modalities, and problems to be solved. It remains unknown, however, which of these factors have specifically contributed to the positive outcomes. This leads to interesting subjects for future research, which will be presented in the next section.

Directions for future research

The findings of this dissertation give rise to a number of potentially interesting topics for further research. Most importantly, the results provide sufficient grounds for future research within general education classrooms, in order to investigate methods for enhancing development in early numeracy, and to assess these differently from the remedial instructions offered in the present study. It is furthermore recommended to include a general intervention condition, carried out in small groups, to be compared to the early numeracy condition. It is possible, although not likely, that the early numeracy gains were partly the result of special treatment more generally, rather than the specific number-related activities. Therefore, in the ideal design, this condition would exist alongside a care-as-usual control condition, as was done in the current study (Ranjith, 2005). Besides that, five themes for future research could be distinguished.

First, in most intervention studies, and also in the studies described in this dissertation, programs are offered spanning multiple domains of early numeracy. It remains unknown, however, which aspects, either concerning content or instructional components, specifically contribute to the positive outcomes. Experimental studies in which, for example, the domains are split and trained separately can provide insight in the causal relations between early numeracy and math development, as well as reveal promising subjects for inclusion in the educational setting. Although there have been some studies focusing on specific aspects of early numeracy, such as counting, estimating, or reasoning skills (Fuchs et al., 2010; Pasnak et al., 2009; Siegler & Ramani, 2009), evidence for other domains within early numeracy is lacking. The same applies to varying instructional or educational components, which can provide evidence for the effectiveness of these constituents, especially regarding generalization or transfer effects of remedial interventions.

A second recommendation for future research, which is related to the first one, is to examine which aspects of early numeracy are likely to develop as results of the offered intervention. In this dissertation, no attempt was made to operationalize different constructs within early numeracy ability, and staying as close as possible to the manner in which language and numeracy ability is measured within an educational setting in Dutch kindergartens was considered important (Lansink, 2009; Van Luit & Van de Rijt, 2009). However, it would be highly interesting to find effects on specific constructs. Further studies are needed to understand the developmental differences in subcomponents of early numeracy performance in children at risk of developing math learning difficulties.

Third, the results of this dissertation focused on predictors influencing early numeracy development and revealed the need forfuture research that would productively explore how individual differences in cognitive and linguistic resources affects the development on early numeracy skills for at-risk kindergartners. In this study, some specific explaining variables were chosen. The set of predictors, however, was limited and did not include, for example, processing time (e.g., Berg, 2008), attention (e.g., Swanson, 2011), shifting (e.g., McLean & Hitch, 1999), and inhibition (e.g., Bull & Scerif, 2001). Moreover, environmental and educational variables, such as SES and home language (Anders et al., 2012) or the quality of the home and preschool learning environment (e.g., Melhuish et al., 2008) may also play a role.

Fourth, the studies in this dissertation specifically focus on children perceived to be at risk of developing math learning difficulties. The used selection criteria across the studies were not equal. In intervention studies, children scoring below average were selected (for the feasibility of the design on school level), whereas in the other studies the selection criterion was more strict. These differences should be taken into account when directly comparing the results of this dissertation with other and future studies. It is recommended that a similar study be carried out using the same intervention, but only including children scoring very low on a standardized early numeracy test.

With regard to the predictors of low early numeracy, a final recommendation will be provided. For both the discussion around which working memory component is more important in early numeracy as well as the discussion around whether symbolic or non-symbolic skills is a better precondition for early numeracy skills, growing evidence is available for typically developing children (e.g., Kolkman et al., 2013; Sasanquie, Göbel, Moll, Smets, & Reynvoet, 2013). Future research is necessary to investigate the specific relations of these predictors with early numeracy in children at risk of developing mathematical learning difficulties.

Practical implications

The aims addressed in this dissertation mainly concern practically-related questions. Therefore, it is imperative to look into the implications for practice in the educational kindergarten setting.

One of the main findings of this dissertation concerns the importance of early numeracy, and the related concept of working memory, as predictors of math learning difficulties. On a practical level, this implies that the factors considered in the present study, especially verbal working memory, symbolic comparison skills, and math language, might be good predictive measures for identifying children at risk of developing learning difficulties at an early stage. Clinicians are encouraged to take those abilities into account when assessing children who are expected to be at risk of developing math learning disabilities. It could be helpful to include these predictors, or underlying factors, in screening batteries or other diagnostic instruments in kindergarten. Apart from facilitating the identification of at-risk children, this will also give useful insights into possible gaps in the skills of these children. Whereas specific early numeracy measures and working memory tasks are beginning to become available (e.g., AWMA; Alloway, 2007), less standardized options tend to be used to measure the mastery of specific language being important to understand mathematical transformations. Nowadays, measuring general language achievement is part of the assessment system in most kindergartens (Lansink, 2009). Unfortunately, these general language skills are insufficient for identifying gaps that can influence early numeracy development and the origin of math learning difficulties, so designing a more specific test on math language could be highly valuable.

Another finding of this dissertation is the confirmation that remedial support for at-risk kindergartners is possible and effective. Building on this finding and results from many prior studies (e.g., Baroody et al., 2009), the use of numeracy interventions especially for children with low early numeracy skills, such as *The road to mathematics*, is advisable, as many such children enter into first grade with lagging skills compared to their typical achieving counterparts. Another focus of intervention for children at-risk for math learning difficulties is working memory. The results in this dissertation emphasize the importance of stimulating working memory to prepare kindergartners for formal mathematic instruction in first and second grades. Although the effects of working memory training can be questioned (Hulme & Melby-Lervåg, 2012), some studies indeed demonstrate generalization effects of working memory training with regard to early math learning (e.g. Holmes, Gathercole, & Dunning, 2009).

The final implication concerns the use of specific math language in home and kindergarten environments. Besides testing specific math concepts, the importance of specific math language should be better acknowledged within educational settings. In other words it should be included and more deeply embedded within the curriculum. Following Lansdell (1999), there are several recommendations for teachers to avoid serious misunderstandings in children's learning of this math language, including the awareness of "ambiguous" words, the consciousness and consistency of their own use, assessments of children's understanding of new concepts and the introduction of new meaning in context once the concepts are understood. The research in this dissertation can contribute to an increased level of awareness among practitioners about the importance of specific math language and the need to use this language when offering instruction to young children at risk of developing math learning difficulties.

Final conclusion

To summarize, three main conclusions can be drawn. The first conclusion is that early numeracy is an integral part of the developmental route towards mathematics and therefore is an important, whether or not the most important, predictor of which children will experience difficulties in learning mathematical abilities during primary school. The second conclusion is that there are several predictors, or underlying factors, involved in the development of early numeracy in weak performing kindergartners. The development of early numeracy in those children is facilitated by verbal working memory, symbolic comparison skills and specific math language. The third conclusion is that remedial intervention during kindergarten is beneficial for young children who may be at risk of having math difficulties. Ideally, the provision of adequate assistance starting halfway the first year of kindergarten can assist children in reaching an acceptable level of early numeracy when starting formal math education in the first grade.

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Samenvatting
(Dutch summary)

Leren rekenen is één van de belangrijkste kerndoelen in het basisonderwijs. Wanneer een kind problemen ervaart bij het leren rekenen kan dit nadelige gevolgen hebben voor het schools functioneren en het dagelijks leven van het kind. Problemen bij het uitvoeren van rekenkundige handelingen ontstaan zelden plotseling, maar kennen hun oorsprong veelal jaren eerder. Het vroeg identificeren van kinderen met een risico tot het ontwikkelen van rekenproblemen maakt vroegtijdige interventie mogelijk. De kans op problemen wordt daarmee aanzienlijk gereduceerd. Eén van de voornaamste factoren voor vroege signalering van risicokinderen in de kleuterperiode is voorbereidende rekenvaardigheid. Deze vaardigheid omvat een scala aan deelvaardigheden, zoals het (verbaal) tellen, het kennen van getalsymbolen en het herkennen en vergelijken van (on)gestructureerde hoeveelheden. Een kind zal de meeste deelvaardigheden moeten beheersen, wanneer het met het daadwerkelijke rekenen in groep 3 begint. Voor de meeste kinderen is het leren van deze deelvaardigheden een natuurlijk proces, dat plaatsvindt tijdens het (in)formeel leren in de thuis- en schoolomgeving.

Deze dissertatie richt zich op de kinderen bij wie deze ontwikkeling niet als vanzelfsprekend tot stand komt bij het volgen van het reguliere kleutercurriculum. Deze kinderen lopen het risico om, op het gebied van rekenen, achter te blijven gedurende hun lagere schoolperiode en zelfs daarna. Het onderzoek dat in deze dissertatie wordt beschreven tracht bij te dragen aan de kennis over deze specifieke groep kinderen door middel van drie doelen: (1) het voorspellen van een vertraagde of verstoorde rekenontwikkeling op basis van voorbereidende rekenvaardigheid; (2) het identificeren van onderliggende factoren in de ontwikkeling van voorbereidende rekenvaardigheid; en (3) het exploreren van de effecten van een remediërende interventie voor kinderen met een achterstand in de voorbereidende rekenvaardigheid.

Doel 1: Het belang van voorbereidende rekenvaardigheid

Uit eerder onderzoek blijkt dat kleuters grote verschillen laten zien in hun beheersing van voorbereidende rekenvaardigheid. In hoofdstuk 2 is nagegaan of op basis van deze diversiteit voorspeld kan worden welke kinderen rekenproblemen in groep 4 zullen gaan krijgen. Bovendien is onderzocht of de executieve functies *shifting*, *inhibitie* en *werkgeheugen* (ook wel updating genoemd) bijdragen aan deze voorspelling. De leerlingen, die participeerden in het longitudinale onderzoek, zijn geclassificeerd in drie categorieën op basis van hun rekenscores in groep 3 en 4; normaal ontwikkelende kinderen, kinderen met een risico op rekenproblemen en kinderen met persistente rekenproblemen. Vervolgens zijn discriminantanalyses uitgevoerd om te toetsen of de groepsindeling, en met name de categorie kinderen met persistente rekenproblemen, voorspeld kan worden. Hieruit blijkt dat op basis van voorbereidende rekenvaardigheid en werkgeheugen met 66.7% zekerheid voorspeld kan worden welke kinderen rekenproblemen zullen ervaren tijdens de eerste twee jaar van het formele rekenonderwijs. Werkgeheugen, het vermogen om informatie simultaan op te slaan en te herzien, blijkt een belangrijke voorspeller te zijn voor rekenproblemen. Inhibitie en shifting blijken, in tegenstelling tot de verwachting, geen voorspellers van rekenproblemen te zijn. Werkgeheugen wordt als belangrijk gezien voor (voorbereidend) rekenen omdat essentiële informatie, bijvoorbeeld uit een contextsom of de tussenstappen bij een opgave, constant moet worden opgeslagen en gemanipuleerd tijdens het uitvoeren van een rekentaak.

De resultaten van hoofdstuk 2 laten daarmee zien dat zowel voorbereidende rekenvaardigheid als werkgeheugen belangrijke indicatoren zijn om kinderen met het risico op rekenproblemen te signaleren en dragen daarmee bij aan de aanname dat voorbereidende rekenvaardigheid integraal deel uitmaakt van de ontwikkelingsroute naar rekenen. Op basis van de bevindingen kan gesteld worden dat het in de onderwijspraktijk zinvol kan zijn om, naast voorbereidende rekenvaardigheid, een werkgeheugentoets als maat te gebruiken om kinderen met een risico op rekenproblemen op jonge leeftijd te identificeren. Aangezien er de laatste jaren steeds meer toegang is tot screeningsbatterijen en diagnostische instrumenten op dit gebied, worden leerkrachten en intern begeleiders aangemoedigd om voorbereidende rekenvaardigheid en werkgeheugen in kaart te brengen, wanneer er een vermoeden bestaat van een reken- of algemene leerachterstand.

Hoofdstuk 2 heeft de basis voor de andere twee doelen van deze dissertatie gevormd: het toetsen van voorspellende of onderliggende factoren die een lage voorbereidende rekenvaardigheid beïnvloeden en het exploreren van de interventiemogelijkheden voor kinderen met het risico tot het ontwikkelen van rekenproblemen. Beide doelen zijn onderzocht in een grootschalig longitudinaal onderzoek. In dit onderzoek zijn 1040 kinderen 2 jaar gevolgd van halverwege groep 1 tot halverwege groep 3. De rekenkundige, cognitieve en linguïstische vaardigheden van deze kinderen zijn op vijf verschillende momenten getoetst. Ten behoeve van het derde doel, het testen van de effectiviteit van een interventie, zijn de kinderen op basis van hun prestaties op het eerste meetmoment (halverwege groep 1) ingedeeld in een benedengemiddelde groep en een bovengemiddelde groep (de referentieconditie). Kinderen in de benedengemiddelde groep zijn aselect toegewezen aan één van de drie condities. Kinderen in de eerste conditie ontvingen gedurende anderhalf jaar instructie op basis van het speciaal voor dit doel ontwikkelde remediërend programma Op weg naar rekenen, kinderen in de tweede conditie kregen de korte versie van dit programma gedurende een half jaar aangeboden en kinderen in de derde conditie vormden de controleconditie.

Doel 2: Factoren in de ontwikkeling van een lage voorbereidende rekenvaardigheid

Het tweede doel was het toetsen van factoren die invloed zouden kunnen hebben op een vertraagde of verstoorde ontwikkeling van voorbereidende rekenvaardigheid. Inzicht in deze factoren kan helpen de ontwikkeling van een beperkte voorbereidende rekenvaardigheid beter te begrijpen. In hoofdstuk 3 zijn de factoren werkgeheugen, vergelijksvaardigheden en specifieke rekentaal getoetst als voorspellers van ontwikkeling in voorbereidende rekenvaardigheid bij zwak presterende kleuters. Dat zijn kleuters die op een voorbereidende rekenvaardigheidstoets een score behalen onder het 15de percentiel.

Werkgeheugen is belangrijk voor het opslaan en reviseren van informatie tijdens het uitvoeren van rekenactiviteiten. In deze dissertatie wordt onderscheid gemaakt tussen visueel en verbaal werkgeheugen. Visueel werkgeheugen kan omschreven worden als het systeem dat zich richt op het verwerken van visueel aangeboden informatie, terwijl het verbaal werkgeheugen verantwoordelijk is voor het opslaan en verwerken van auditief aangeboden informatie. Vergelijkingsvaardigheden refereren aan het vermogen om te kunnen discrimineren tussen aantallen. Hierbinnen wordt onderscheid gemaakt tussen het vergelijken van non-symbolische hoeveelheden (bijvoorbeeld stippen) en het vergelijken van symbolische representaties (de Arabische getalsymbolen). Specifieke rekentaal, ten slotte, omvat dat gedeelte van taal dat direct aan rekenen is gerelateerd. Het gaat hierbij om begrippen zoals *meer*, *minder*, *hoger* en *lager*, die gebruikt kunnen worden om objecten of aantallen te vergelijken of te classificeren, maar ook concepten zoals *heel* en *half*, of meer spatiële concepten zoals *boven*, *onder* of *tussen*.

Bovengenoemde factoren zijn op verschillende momenten in de kleuterschoolperiode gemeten. Voorbereidende rekenvaardigheid is op vier verschillende momenten gemeten, tweemaal in groep 1 en tweemaal in groep 2. Latente groeimodellen, waarbij gecorrigeerd is voor de geneste structuur van de data, laten zien dat alle getoetste factoren een belangrijke rol spelen in het verwerven van voorbereidende rekenvaardigheid bij zwak presterende kleuters. Daarbij hebben het visueel werkgeheugen en non-symbolische vergelijkingsvaardigheden vooral invloed op het algemene niveau (de intercept) en het verbaal werkgeheugen en symbolische vergelijkingsvaardigheden vooral invloed op de vooruitgang gedurende de twee jaar (de slope). Het beheersen van specifieke rekentaal blijkt de sterkste voorspeller van zowel het algemene niveau als de mate van groei in voorbereidende rekenvaardigheid. Dit betekent dat kinderen met een grotere verbale werkgeheugencapaciteit, een beter ontwikkeld begrip van de waardes van getalsymbolen en kennis van specifieke rekentaal zich sneller ontwikkelen op het gebied van voorbereidende rekenvaardigheid.

De grote rol van het verbaal werkgeheugen kan verklaard worden door de talige aard van de gebruikte toets, maar kan vermoedelijk met minstens evenveel recht worden toegeschreven aan de specifieke groep kinderen, die is geselecteerd op basis van problemen in voorbereidende rekenvaardigheid. Het verbaal werkgeheugen is namelijk in eerder onderzoek als belangrijke voorspeller aangetoond voor rekenuitkomsten bij rekenzwakke kinderen. De grote rol van symbolische vergelijkingsvaardigheden als belangrijke voorspeller van ontwikkeling sluit aan bij eerder onderzoek, dat zich specifiek richt op kinderen met rekenproblemen en laat zien dat deze kinderen moeite hebben met het vergelijken van getalsymbolen, maar niet met het vergelijken van stippenaantallen. Zwakke kinderen lijken dus alleen beperkt te zijn in hun vermogen om hoeveelheden op basis van getallenkennis te discrimineren en niet in het vermogen om non-symbolische aantallen te verwerken.

Om de rol van specifieke rekentaal beter in kaart te brengen, met name hoe deze rol zich verhoudt ten opzichte van de algemene taalbeheersing, is in aanvullende analyses onderzocht wat de betekenis is van specifieke rekentaal binnen de ontwikkelingsrelatie tussen algemene taal en lage voorbereidende rekenvaardigheid bij kleuters. In deze studie, gerapporteerd in hoofdstuk 4, zijn deze relaties expliciet getest binnen een design waarbij algemene taalvaardigheden en voorbereidende rekenvaardigheid viermaal zijn getoetst in groep 1 en 2 en specifieke rekentaal eenmaal in groep 2. De multivariate groeimodellen geven aanleiding tot twee belangrijke bevindingen. Ten eerste tonen ze het bestaan van een wederkerige relatie tussen de ontwikkeling van taal en de ontwikkeling van rekenen bij risicokinderen aan en laten ze zien dat het algemene taalniveau de ontwikkeling in voorbereidende rekenvaardigheid beïnvloedt. Ten tweede blijkt specifieke rekentaal een mediërende factor te zijn binnen de ontwikkelingsrelatie van algemene taal en voorbereidende rekenvaardigheid.

De ontwikkeling van voorbereidende rekenvaardigheid blijkt bij deze kinderen in grote mate afhankelijk te zijn van taalbeheersing en met name van specifieke rekentaal.

Dit impliceert dat specifieke rekentaal meer aandacht verdient in de leeromgeving van jonge kinderen zowel thuis als op school. Rekentaal zou daarom explicieter geïncludeerd en ingebed kunnen worden in het huidige kleuteronderwijs en leerkrachten zouden zich in hogere mate bewust moeten zijn van het belang van specifieke rekentaal en de noodzaak deze taal expliciet aan te bieden. Bovendien is het aan te bevelen om naast algemene toetsen voor taal en voorbereidende rekenvaardigheid, zoals deze in het kleuteronderwijs gebruikt worden, ook een meer specifieke toets voor rekentaal te gebruiken.

Om ook de rol van werkgeheugen nader te onderzoeken is de voorbereidende rekenvaardigheid van kinderen met een beperkt werkgeheugen onderzocht. In twee studies, beiden gerapporteerd in hoofdstuk 7, is getoetst of kinderen met een beperkt werkgeheugen in het nadeel zijn bij het leren rekenen ten opzichte van hun leeftijdgenoten met een normaal ontwikkeld werkgeheugen. De kinderen zijn op basis van een werkgeheugenscreening ingedeeld in vier groepen op basis van de specificiteit van hun beperkingen in het werkgeheugen. Op die manier is het mogelijk om kinderen zonder problemen in het werkgeheugen, kinderen met problemen in het verbaal werkgeheugen, kinderen met problemen in het visueel werkgeheugen en kinderen met problemen in het verbaal en het visueel werkgeheugen te vergelijken. Uit de eerste studie blijkt dat kinderen met een beperkt werkgeheugen inderdaad meer problemen ervaren en een minder snelle ontwikkeling doormaken in voorbereidende rekenvaardigheid. Uit de tweede studie blijkt dat kinderen met beperkingen in het visueel of verbaal werkgeheugen geen problemen ervaren in specifieke numerieke vaardigheden. Beperkingen in het verbaal werkgeheugen leiden bijvoorbeeld niet tot afwijkingen in de beheersing van de telrij of andere verbale numerieke vaardigheden. Beperkingen in het visueel werkgeheugen leiden op hun beurt niet tot problemen in het begrijpen van de getalsymbolen. Kinderen met beperkingen in zowel het verbaal als het visueel werkgeheugen ervaren echter wel meer problemen in numerieke taken.

Doel 3: Remediërende hulp aan kleuters met een achterstand in voorbereidende rekenvaardigheid

Ten behoeve van het derde doel is een specifiek remediërend programma voor kleuterrekenen ontwikkeld in samenwerking met een groot aantal professionals uit het onderwijsveld. Dit programma – *Op weg naar rekenen* – is gebaseerd op theoretische bevindingen en empirische uitkomstmaten die effectief gebleken zijn voor kinderen met een beperkte voorbereidende rekenvaardigheid. In drie studies, beschreven in de hoofdstukken 5, 6 en 8, is getoetst of *Op weg naar rekenen* een effectief programma is om voorbereidende rekenvaardigheid van risicokleuters te bevorderen. Hoewel de drie studies van elkaar verschillen qua onderzoeksopzet en (statistische) methodieken, kan geconcludeerd worden dat *Op weg naar rekenen* een effectief programma is voor remediërende ondersteuning op het gebied van voorbereidende rekenvaardigheid bij kleuters. Dat het stimuleren van zwakke kleuters door middel van gestructureerde interventie positieve effecten op kan leveren was reeds bekend. Er is echter aanzienlijk minder informatie beschikbaar over de effecten van interventies zoals *Op weg naar rekenen*, die speciaal ontwikkeld zijn voor kinderen met een risico tot het ontwikkelen van rekenproblemen of voor kinderen met een beperkt werkgeheugen.

De eerste studie, hoofdstuk 5, fungeert als pilotstudie waarin gebruik is gemaakt van een verkorte versie van het programma. De prestaties van de interventiekinderen, die het programma 8 weken hebben gevolgd, zijn vergeleken met gematchte controlekinderen en kinderen met een bovengemiddelde voorbereidende rekenvaardigheid. Ondanks dat alle drie groepen vooruitgang hebben geboekt tijdens de periode van 8 weken, is er bij de interventiekinderen sprake van de grootste vooruitgang. Voor de kinderen met zeer lage scores is dit effect echter niet significant. De pilotversie is dus alleen effectief gebleken voor kinderen met een enigszins benedengemiddeld niveau van voorbereidende rekenvaardigheid.

In de tweede studie, hoofdstuk 6, zijn de effecten van twee versies, een complete versie van 1.5 jaar en een korte versie van 0.5 jaar, van *Op weg naar rekenen* in kaart gebracht. De effecten zijn vergeleken met de opbrengsten van het reguliere curriculum bij kinderen met een benedengemiddelde voorbereidende rekenvaardigheid (controleconditie) en bij normaal presterende kinderen (referentieconditie). De kinderen die, door leerkrachten van de eigen school, één van de twee versies hebben onderwezen gekregen, blijken direct na afloop van het programma (eind groep 2) en een half jaar na de afronding (halverwege groep 3) hoger te scoren op voorbereidende rekenvaardigheid. Bovendien zijn zij beter in het uitvoeren van eenvoudige optelsommen en het oplossen van algemene rekentaken, dan de kinderen die het reguliere curriculum hebben gevolgd. Zodoende lijkt er bij de interventiekinderen sprake te zijn van internalisatie en generalisatie van de opgedane kennis uit het programma naar meer complexe vaardigheden, die geen onderdeel van het programma uitmaken. Dit geldt met name voor de kinderen die het programma gedurende 1.5 jaar hebben gevolgd. Wanneer gecorrigeerd wordt voor het niveau bij aanvang van de studie, blijkt hun prestatie op voorbereidende rekenvaardigheid direct na afloop van het programma en hun prestatie op de Cito rekentoets midden groep 3 hoger te liggen dan dat van de kinderen in de referentieconditie.

Ten slotte is in hoofdstuk 8 nagegaan of *Op weg naar rekenen* ook effectief is voor kinderen met een beperkt werkgeheugen. Dit onderzoek richt zich specifiek op de periode halverwege groep 1 tot en met halverwege groep 2 en laat zien dat kinderen met beperkte werkgeheugencapaciteit in dezelfde mate profiteren van het aangeboden programma als hun leeftijdsgenoten met een normaal ontwikkeld werkgeheugen. Hoewel het gemiddelde niveau van voorbereidende rekenvaardigheid bij de kinderen met een beperkt werkgeheugen ondanks gevolgde interventie lager blijft dan het niveau van kinderen met een normaal ontwikkeld werkgeheugen, indiceren de bevindingen dat remediërende ondersteuning waardevol is voor zowel kinderen met een gemiddelde werkgeheugencapaciteit als kinderen met een beperkt werkgeheugen.

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Tell the repo man and the stars above; you're the one I love!

About the author

Curriculum vitae

Sylke Toll was born on March 4, 1987 in Boxmeer, the Netherlands. She obtained her high school degree (atheneum) in 2005 from the Merletcollege in Cuijk, after which she attended Utrecht University. In 2009 she obtained her clinical master degree in special education (orthopedagogiek) with honours. She also acquired the diagnostic registration of the NVO. From 2010 until 2014 Sylke worked as a PhD student at the research group Educational and Learning Sciences (ELS) at Utrecht University. She coordinated the data collection of the large-scale study, which resulted in this dissertation, organized six training days for the involved teachers and gave several presentations and lectures to scientists and practitioners in the field of early numeracy education. Presenting her research at international conferences resulted in two awards for best presentations held by a PhD student at the Biennal meeting of EARLI SIG 15 in 2010 (Frankfurt) and 2012 (Utrecht). Together with Hans van Luit, she developed *The road to mathematics*, a remedial program for early numeracy. During her PhD trajectory, Sylke was actively involved in the PhD council and the Graduate School Educational Committee within the faculty of Social and Behavioral Sciences. In September 2012 she spent a month at the University of Delaware, USA, to collaborate with Prof. dr. Nancy C. Jordan.

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Awards

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