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Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade

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ABSTRACT

This longitudinal study examined the relationship between working memory and individual differences in mathematics. Working memory measures, comprising the phonological loop, the visuospatial sketchpad, and the central executive, were administered at the start of first grade. Mathematics achievement was assessed 4 months later (at the middle of first grade) and 1 year later (at the start of second grade). Working memory was significantly related to mathematics achievement in both grades, showing that working memory clearly *predicts* later mathematics achievement. The central executive was a unique predictor of both first- and second-grade mathematics achievement. There were age-related differences with regard to the contribution of the slave systems to mathematics performance; the visuospatial sketchpad was a unique predictor of first-grade, but not second-grade, mathematics achievement, whereas the phonological loop emerged as a unique predictor of second-grade, but not first-grade, mathematics achievement.

Introduction

Working memory is an important factor in understanding individual differences in mathematics achievement in children. Research on the role of working memory in mathematics performance draws

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mainly on studies of children with mathematical disabilities, indicating that deficits in mathematics are linked to poor working memory (Bull, Johnston, & Roy, 1999; Gathercole & Pickering, 2000a; Geary, Hamson, & Hoard, 2000; McLean & Hitch, 1999; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989; Swanson & Beebe-Frankenberger, 2004; Swanson & Sachse-Lee, 2001; van der Sluis, van der Leij, & de Jong, 2005). Although there are many fewer studies in typically developing children, these also indicate that working memory plays an important role in (individual differences in) typical mathematics performance (Adams & Hitch, 1997; Bull & Scerif, 2001; Gathercole & Pickering, 2000b; Hecht, Torgesen, Wagner, & Rashotte, 2001; Holmes & Adams, 2006; Swanson & Kim, 2007).

The majority of these correlational studies in typically and atypically developing children are cross-sectional. Such a design does not allow us to determine the nature of the relationship between working memory and mathematics achievement. Therefore, we aimed to investigate whether working memory is a *precursor* of individual differences in mathematics achievement. We assessed measures of working memory at the beginning of first grade. Consequently, these assessments were not influenced by mathematics learning in primary school and allowed us to examine whether later mathematics achievement can be *predicted* by working memory. In the remainder of this section, the different components of working memory and their relationship with individual differences in mathematics are described first. After that, the design of the current study is presented.

Components of working memory

Baddeley's influential three-component model of working memory (Baddeley, 1986, 2003; Baddeley & Logie, 1999) served as our framework to examine the influence of different working memory components on mathematics achievement. At the core of Baddeley's model is the central executive, which is responsible for the control, regulation, and monitoring of complex cognitive processes. The model also encompasses two subsidiary subsystems of limited capacity that are used for temporary storage of phonological information (i.e., the phonological loop) and visual and spatial information (i.e., the visuospatial sketchpad). These two subsystems, also called slave systems, are used only for passive information storage and can be considered as analogous to the original short-term memory concept. Both subsystems are in direct contact with the central executive. These subsidiary systems are typically assessed by means of classic short-term memory tasks such as the recall of digits (e.g., Digit Span) and locations (e.g., Block Recall). Central executive ability is generally investigated by means of complex span tasks that require both storage and simultaneous processing of information such as the well-known Listening Span task (Daneman & Carpenter, 1980) and Counting Span task (Case, Kurland, & Goldberg, 1982). This tripartite structure of working memory is supported by converging evidence from brain imaging, neuropsychological, and cognitive developmental studies (Baddeley, 2003). Most interesting, a large-scale cognitive study on the working memory structure in children showed that this three-component model was confirmed in 6- to 15-year-olds (Gathercole, Pickering, Ambridge, & Wearing, 2004; see also Alloway, Gathercole, & Pickering, 2006). In a recent reformulation of the model, Baddeley (2003) proposed a fourth component, the episodic buffer, which involves a temporary multimodal storage component. Due to limited developmental research regarding this fourth component, we focused only on the first three components.

Components of working memory and individual differences in mathematics

Each component of Baddeley's working memory model is thought to have a specific role in mathematics performance (see DeStefano & Lefevre, 2004, for a review). Evidence from dual-task studies has consistently shown the involvement of the central executive in arithmetic, indicating that this component is responsible for the monitoring and coordination of different steps during arithmetic problem solving (Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007b; Imbo, Vandierendonck, & De Rammelaere, 2007). Turning to the slave systems, it has been shown that the phonological loop plays an important role in arithmetic, presumably in counting or in keeping track of the operands while calculating (Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007b; Noël, Seron, & Trovarelli, 2004). Studies on the visuospatial sketchpad are much less common, but this component appears to be involved in subtraction, where numbers are assumed to be processed in a magnitude code akin to a mental number line (Lee & Kang, 2002), and in multidigit calculation, where the visuospatial sketchpad might be responsible for spatial aspects of calculation, such as number alignment and carrying (Trbovich & Lefevre, 2003). Although dual-task experiments in children are rare, McKenzie, Bull, and Gray (2003) showed the involvement of the phonological loop and the visuospatial sketchpad in arithmetic with 6- to 9-year-olds.

Most of the evidence on the influence of working memory on mathematics performance in children comes from correlational studies. These studies have indicated that the central executive contributes to individual differences in children's mathematics performance (Bull & Scerif, 2001; Gathercole & Pickering, 2000b; Holmes & Adams, 2006; Passolunghi, Vercelloni, & Schadee, 2007; Swanson & Kim, 2007). Moreover, mathematical disabilities have been related to deficits in the central executive (Gathercole & Pickering, 2000a; Geary et al., 2000; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989; Swanson & Beebe-Frankenberger, 2004), and mathematical precociousness has been associated with higher central executive performance (Swanson, 2006). Gathercole and Pickering (2000b) and Swanson and Kim (2007) also showed that this association between the central executive and mathematics performance remained when controlling for phonological loop ability, pointing to a unique contribution of the central executive to mathematics performance.

Although there is ample evidence for the contribution of executive working memory resources to mathematics performance, the role of the slave systems seems to be less clear. Hecht and colleagues (2001) showed that the phonological loop was a unique predictor of mathematics achievement in primary school children. A recent study by Swanson and Kim (2007) demonstrated that phonological storage was uniquely related to mathematics performance in 6- to 10-year-olds. However, not all studies have reported evidence in favor of this relationship. For example, Gathercole and Pickering (2000b) showed that phonological loop ability was correlated with mathematics performance in 7- to 8-year-olds, but this association disappeared when controlling for central executive ability (see also Holmes & Adams, 2006). Bull and Johnston (1997) demonstrated that 7-year-old low mathematics achievers and high mathematics achievers differed on measures of the phonological loop, but this difference disappeared when controlling for reading ability. Similarly, studies on children with mathematical disabilities have generally revealed no impairments in phonological loop ability (e.g., Geary et al., 2000).

Research on the influence of the visuospatial sketchpad on mathematics development has gained relatively little attention. Initial evidence came from the observation that children with mathematical disabilities showed impairments on visuospatial sketchpad tasks (Gathercole & Pickering, 2000a; McLean & Hitch, 1999; van der Sluis et al., 2005; but see Bull et al., 1999). Recent studies have reported significant associations between the visuospatial sketchpad and individual differences in mathematics achievement at various ages throughout primary school (Holmes & Adams, 2006; Holmes, Adams, & Hamilton, 2008; Jarvis & Gathercole, 2003). Moreover, it appears that the contribution of the visuospatial sketchpad to mathematics achievement differs as a function of age and that this contribution may be especially important during the initial stages of mathematics learning. For example, Rasmussen and Bisanz (2005) showed that the visuospatial sketchpad was associated with mathematics in preschoolers, but this association disappeared in first graders. Recent reports by Holmes and Adams (2006) and Holmes and colleagues (2008) indicated that the visuospatial sketchpad has a stronger role in 7- and 8-year-olds' mathematics performance compared with that of 9- and 10-year-olds. Consistent with this, the dual-task experiment by McKenzie and colleagues (2003) revealed that the arithmetic performance of young children (6- and 7-year-olds) was seriously affected by concurrent visuospatial disruption, whereas the latter had only a mild impact on the arithmetic performance of older children (8- and 9-year-olds). All of this suggests that the contribution of the visuospatial sketchpad to mathematics achievement is age related. Younger children may have a greater reliance on visuospatial strategies to solve arithmetic problems, whereas older children may use verbal solution strategies, such as retrieval, that do not require involvement of the visuospatial sketchpad. However, the aforementioned studies were cross-sectional, using different groups of children at different ages. This necessitates a replication with a longitudinal design in the same sample of children. The longitudinal design of our study, therefore, extended these findings by examining the association between working memory and mathematics over different time points in one group of children.

Some studies have investigated the influence of working memory on mathematics with a longitudinal correlational design. Hecht and colleagues (2001) examined the influence of phonological loop ability on mathematics performance during children's second- through fifth-grade school years. They showed that the phonological loop was a unique predictor of mathematics performance, but this effect was limited to the second- and third-grade time interval. Unfortunately, no other components of working memory were investigated. Two other studies (Noël et al., 2004; Passolunghi et al., 2007) investigated whether initial measures of working memory, assessed at the start of first grade, predicted later mathematics achievement. Noël and colleagues (2004) showed that both the central executive and the phonological loop predicted single-digit addition 4 months later. Passolunghi and colleagues (2007) revealed that the central executive, and not the phonological loop, was a significant unique predictor of individual differences in mathematics achievement at the end of first grade. Unfortunately, none of these studies included measures of visuospatial sketchpad ability. Hence, the predictive value of the visuospatial sketchpad remains unclear.

The selection of working memory measures limited to the phonological loop and the central executive in the aforementioned longitudinal studies might have overemphasized the role of these two components in explaining mathematics performance. The unique role of the working memory components in mathematics can, indeed, be determined only when all working memory components are included. Moreover, such an investigation should also incorporate other variables that may influence mathematics performance. Clearly, early levels of mathematics are one of the most powerful sources of individual differences in later mathematics achievement (for a similar rationale in the domain of reading, see Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). The inclusion of the autoregressive effect of prior mathematics level is important to find out whether working memory independently influences growth in mathematics achievement during the developmental period under investigation; if working memory uniquely contributes to individual differences in mathematics performance, then it should explain individual differences in mathematics that are independent of prior mathematics level. To the best of our knowledge, there are no studies that have examined the influence of initial level of mathematics performance on the association between working memory and later mathematics achievement.

The current study

We aimed to examine whether initial measures of working memory predicted subsequent mathematics achievement by conducting a longitudinal correlational study. We also sought to determine the unique contributions of working memory components in explaining variability in mathematics performance in first and second grades. The current study extended previous research in three ways. First, our study was longitudinal with the working memory data collected before mathematics achievement data, allowing us to determine whether working memory *predicted* the acquisition of later mathematical skills. Second, unlike existing longitudinal studies, all components of working memory were investigated simultaneously. Finally, we investigated the autoregressive effect of early mathematics achievement in addition to working memory on subsequent mathematics achievement in order to determine the unique contribution of working memory in the prediction of mathematics achievement.

To examine whether working memory predicted mathematics achievement, assessments of all three working memory components—the phonological loop, the visuospatial sketchpad, and the central executive—were administered at the beginning of first grade, that is, at the start of formal schooling. Mathematics achievement data were collected 4 months later (in the middle of first grade) and 1 year later (at the start of second grade). A measure of general intellectual ability was also administered to investigate the effect of intellectual ability on the association between working memory and mathematics.

Drawing on previous work, we expected that each working memory component would be a significant predictor of mathematics achievement in first and second grades. We anticipated that the central executive would be a unique contributor to individual differences in mathematics achievement. We also hypothesized that the influence of the visuospatial sketchpad would be most prominent in first grade and would decrease in second grade. Finally, we tested the stringent hypothesis of whether working memory predicted mathematics performance in second grade when first-grade mathematics achievement is taken into account.

Method

Participants

Participants were 106 first graders (63 boys and 43 girls) from five primary schools in Flanders, Belgium. At the start of first grade, when the working memory measures were assessed, the mean age of the children was 6 years 4 months (*SD* = 4 months). First-grade mathematics data were available for 77 children (mean age = 6 years 8 months, *SD* = 8 months). Second-grade mathematics data were available for 83 children (mean age = 7 years 4 months, *SD* = 3 months). Three children did not complete the test of intellectual ability.

Procedure

All participants were tested at their own school during regular school hours. The working memory measures were administered individually in a quiet room during the first month of first grade. The remaining tasks were group-based tests. Mathematics achievement data were collected during the fifth month of the first grade with the Middle First Grade test and during the first month of the second grade with the Start Second Grade test. Intellectual ability was assessed at the start of second grade.

Measures

Working memory

Seven tasks were administered to tap the three components of Baddeley's working memory model (Baddeley, 1986, 2003; Baddeley & Logie, 1999). We selected tasks that have been commonly used in working memory research and in research on working memory and mathematics achievement (Gathercole et al., 2004; Pickering & Gathercole, 2001). Each task involved two practice trials to familiarize the child with the task. All tasks, except the Nonword Repetition Test, adopted the same span procedure. Three trials of each list length or span were presented. A trial was scored as correct if all stimuli of that trial were recalled in the correct order. List length was increased by one stimulus if the child recalled at least two of three trials of the same list length correctly. If the child failed to do this, the task was terminated. Each task started at a list length of two stimuli unless otherwise noted. To minimize the effect of attentional factors on performance, each increase of list length was explicitly announced by the experimenter. Each task yielded a total score equal to the number of trials recalled correctly.

Phonological loop.

Nonword Repetition Test. A nonword repetition test is frequently used as a pure measure of phonological loop ability because the nonwords used in this test involve unfamiliar phonological sequences, and this limits the use of long-term memory representations to support recall (Gathercole, Willis, Baddeley, & Emslie, 1994). The Dutch adaptation (Scheltinga, 2003) of the Children's Test of Nonword Repetition (Gathercole et al., 1994) was used. This test consisted of 48 nonwords that ranged from two to five syllables, with 12 trials for each length. The nonwords, pronounced at a consistent rate, were recorded on a CD by a professional speech therapist, and this recording was presented to the child. Each nonword was presented once, and the child was asked to repeat it immediately after its presentation. In contrast to Gathercole and colleagues (1994), the presentation order was determined by word length, starting with two-syllable words and gradually moving to five-syllable words, to minimize the influence of attentional factors on performance. The total score was determined by the number of nonwords recalled correctly.

Digit Span Forward. This task involved the immediate serial recall of spoken lists of digits between one and nine. For each list length, the stimuli of the first two trials were taken from the Wechsler Intelligence Scale for Children–3rd Edition (WISC-III) (Wechsler, 1992), and a third trial was taken from the

Working Memory Test Battery for Children (WMTB-C) (Pickering & Gathercole, 2001). All lists were recorded by a professional speech therapist at a rate of one digit per second to standardize the assessment. This recording was presented to the child, who was asked to immediately recall the digits in the presented order.

Visuospatial sketchpad.

Block Recall. Block Recall, taken from the WMTB-C (Pickering & Gathercole, 2001), was used to measure the spatial component of the visuospatial sketchpad. The apparatus for this task consisted of a set of nine identical blocks glued to random positions on a board. For each trial, the experimenter tapped a sequence of blocks at a rate of one block per second, and the child was instructed to reproduce the sequence. All sequences were random, and no block was tapped more than once within a sequence.

Visual Patterns Test. The Visual Patterns Test (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999) was used to assess the visual component of the visuospatial sketchpad. This task has been standardized for use with children (Pickering & Gathercole, 2001). In this task, two-dimensional grids of black and white squares were presented. A visual pattern was created by filling half of the squares in a grid. Grids progressed in size, starting with a two-by-two matrix (with two filled cells). List length was defined by the size of the grid; consequently, the number of filled cells within a list length was fixed. Each grid was presented for 3 s, after which it was covered with a blank card. The child was asked to reproduce the pattern immediately by marking the black squares in an empty grid of the same size as the one bearing the pattern just presented. A pattern was correct if all of the squares had been marked in the appropriate positions.

Central executive.

Listening Span. A classic listening span task (Daneman & Carpenter, 1980) adapted to Dutch by van der Sluis and colleagues (2005) was used. In this task, the child was asked to judge the correctness of a series of sentences. The child was further instructed to memorize the last word in every sentence, and to recall those words in the presented order at the end of each trial. An example of a trial was the following: *Baby's slapen in een wieg* [Babies sleep in a cradle], "*correct*"; *De kleur van water is rood* [The color of water is red], "*false*"; recall "*wieg* [cradle], *rood* [red]." All of the sentences used in the task had the same number of words and were obviously correct or false. They all ended on highly frequent consonant–vowel–consonant (CVC) words. All sentences were first recorded on a CD by a professional speech therapist, and this recording was presented to the child. Unlike the task from van der Sluis and colleagues (2005), this task started at a list length of one because otherwise the task was too difficult for children of this young age.

Counting Span. The Counting Span task was originally designed by Case and colleagues (1982), and variations of this task have been frequently used in studies on working memory and mathematics achievement in children (Bull & Scerif, 2001; Hitch & McAuley, 1991; van der Sluis et al., 2005). In this task, the child was presented with a series of white cards, with each card containing 34 noncanonically arranged yellow and green dots. For each trial, the child was asked to count the number of green dots on each of a series of cards and to recall, at the end of the trial, the dot tallies in the order in which the cards were presented. To avoid the use of a subitizing strategy, the number of green dots on a card varied between three and eight, and the child was instructed to count out loud by pointing to each dot in turn.

Digit Span Backward. The construction and administration of this task were similar to those of Digit Span Forward except that the child needed to recall the sequence of auditory presented digits in the reverse order. To ensure that the child understood the concept of "reverse", appropriate feedback was given in the preceding practice trials.

Mathematics achievement

Mathematics achievement was assessed by means of curriculum-based standardized achievement tests for mathematics from the Flemish Student Monitoring System (Dudal, 2001). First-grade mathematics achievement was evaluated by means of the Middle First Grade test. Second-grade mathematics achievement was assessed with the Start Second Grade test. Both tests consisted of 60 items covering number knowledge, understanding of operations, simple arithmetic, word problems, and measurement. The Middle First Grade test involved the number domain 1 to 10, whereas the Start Second Grade test involved the number domain 1 to 20.

Intellectual ability

Raven's Standard Progressive Matrices (Raven, Court, & Raven, 1992) was used as a measure of intellectual ability. For each child, a standardized score ($M = 100$, $SD = 15$) was calculated.

Results

Descriptive statistics

The means, standard deviations, ranges, and maximum possible scores for all administered measures and age are displayed in Table 1. This table indicates that the data were well distributed without ceiling or floor effects. Reliability coefficients of all measures are also presented in this table.

Correlational analyses

Pearson correlation coefficients were calculated to examine the associations between the administered tasks (Table 2). The working memory measures that were thought to measure the same working memory component were significantly interrelated. All working memory measures were significantly correlated with first-grade mathematics achievement except Digit Span Forward and the Visual Patterns Test. All working memory measures were also significantly related to second-grade mathematics achievement except the Visual Patterns Test. Both measures of mathematics achievement were highly and significantly correlated. Intellectual ability was significantly related to all measures except the Visual Patterns Test. Chronological age was not correlated with any of the administered tasks except performance on the Visual Patterns Test.

Prior to the regression analyses, we evaluated whether the three-component structure of working memory as proposed in Baddeley's model fitted with the current data. Therefore, we conducted a confirmatory factor analysis on the working memory tasks with LISREL 8.7 software (Jöreskog & Sörbom, 2004). We hypothesized that the working memory tasks would reflect three factors corresponding to the Phonological Loop (measured by Nonword Repetition and Digit Span Forward), the Visuospatial Sketchpad (measured by Block Recall and the Visual Patterns Test), and the Central Executive (measured by Listening Span, Counting Span, and Digit Span Backward).

Table 1
Descriptive statistics and reliabilities of the administered measures.

	N	*M*	*SD*	Range	Maximum possible	Reliability[a]
Working memory						
Nonword Repetition Test	106	18.75	6.41	0–34	48	.81[b]
Digit Span Forward	106	7.72	1.93	1–12	15	.71[b]
Block Recall	106	6.72	2.51	0–12	15	.77[b]
Visual Patterns Test	106	4.54	2.53	1–13	15	.77[b]
Listening Span	106	3.37	1.72	0–7	15	.64[b]
Counting Span	106	2.51	1.54	0–8	15	.60[b]
Digit Span Backward	106	4.13	1.28	1–8	15	.55[b]
Mathematics achievement						
Middle First Grade	77	49.26	8.30	22–59	60	.90[c]
Start Second Grade	83	46.14	7.72	26–59	60	.90[c]
Raven's matrices	103	105.83	14.24	77–134	150	.90[b]

[a] Cronbach's alpha.
[b] Calculated for the current sample.
[c] Cited from the test manual.

Table 2
Correlation coefficients between the administered measures and age.

	1	2	3	4	5	6	7	8	9	10
1. Nonword Repetition										
2. Digit Span Forward	.57**									
3. Block Recall	.16	.16								
4. Visual Patterns Test	−.06	.08	.21*							
5. Listening Span	.48**	.32**	.36**	.17						
6. Counting Span	.24*	.26**	.27**	.26**	.37**					
7. Digit Span Backward	.41**	.41**	.19*	.06	.34**	.30**				
8. First-grade math achievement	.30**	.21	.51**	.19	.43**	.30**	.38**			
9. Second-grade math achievement	.34**	.43**	.28*	.13	.34**	.39**	.45**	.69**		
10. Raven's matrices	.19	.24*	.26**	.15	.38**	.30**	.29**	.47**	.61**	
11. Age	−.02	.03	.19	.34**	.17	.12	.01	.05	.05	.11

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

The tests of multivariate normality for continuous variables were nonsignificant for both skewness and kurtosis, meeting the multivariate normality assumption required for this kind of analysis. The fit of the model to the data was evaluated by several goodness-of-fit indexes. The chi-square statistic provides a test of the null hypothesis that the proposed model fits the data; a nonsignificant value shows that there is no difference between the model and the data. The comparative fit index (*CFI*) yields an overall measure of fit ranging between 0 and 1; values above .90 are considered to be satisfactory. A final measure of fit is the root mean square error of approximation (*RMSEA*); models with values below .08 are considered to be acceptable, and values below .05 indicate a good fit.

The above-mentioned hypothesized three-factor model provided an acceptable fit to the data, $\chi^2 = 17.60$, $df = 11$, $p = .091$, $CFI = .962$, $RMSEA = .076$. The standardized factor loadings for the Phonological Loop factor were .84 (Nonword Repetition) and .66 (Digit Span Forward), those for the Visuospatial Sketchpad factor were .55 (Block Recall) and .37 (Visual Patterns Test), and those for the Central Executive factor were .68 (Listening Span), .49 (Counting Span), and .56 (Digit Span Backward). This analysis confirmed that for children in the current sample, working memory could be separated into three components. It should be noted that, in line with Baddeley's model, these components were interrelated and the model only fitted when correlations between the different factors were allowed. The Central Executive factor correlated very highly with the Phonological Loop factor ($r = .73$) and the Visuospatial Sketchpad factor ($r = .77$), whereas the latter two factors were only weakly related ($r = .23$). These findings are in accordance with those of Gathercole and colleagues (2004) and Alloway and colleagues (2006), who used similar tasks in similar age groups.

Supported by the confirmatory factor analysis, we aggregated performance on the working memory measures into composite scores.[1] These were created by computing for each task *z* scores based on the total sample. The *z* scores for the tasks that were thought to measure the same working memory component were then averaged to create composite scores for the phonological loop (Nonword Repetition Test and Digit Span Forward), the visuospatial sketchpad (Block Recall and Visual Patterns Test), and the central executive (Listening Span, Counting Span, and Digit Span Backward). The correlations among these composite scores, mathematics achievement, intellectual ability, and age are presented in Table 3. The phonological loop composite was not related to the visuospatial sketchpad composite. Both the phonological loop and visuospatial sketchpad composites were significantly related to the central executive composite. All working memory composites were significantly related to first- and second-grade mathematics achievement. The correlation between the visuospatial sketchpad composite and mathematics achievement was stronger in first grade than in second grade, whereas the correlation between the pho-

[1] When factor scores derived from the confirmatory factor analysis were used as predictors in the regression analyses, formal regression diagnostics revealed high multicollinearity (i.e., variance inflation factors exceeding 10), rendering the estimates of the regression coefficients unreliable (e.g., Cohen, Cohen, West, & Aiken, 2003). Such multicollinearity did not occur when composite scores were entered into the regression analyses (i.e., variance inflation factors < 1.7). Therefore, composite scores were used in all regression analyses.

Table 3
Correlations between composite scores for working memory, mathematics achievement, intellectual ability, and age.

	1	2	3	4	5	6
1. Phonological loop						
2. Visuospatial sketchpad	.12					
3. Central executive	.53**	.39**				
4. First-grade math achievement	.29*	.47**	.52**			
5. Second-grade math achievement	.43**	.27*	.53**	.69**		
6. Raven's matrices	.24*	.26**	.43**	.48**	.61**	
7. Age	.00	.34**	.13	.05	.11	.05

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

nological loop composite and mathematics achievement was stronger in second grade than in first grade. Intellectual ability was significantly related to the central executive composite and the mathematics achievement tests. A smaller, but significant, correlation was observed between intellectual ability and the slave systems.

Regression analyses

Hierarchical regression analyses were calculated for each grade to assess the amount of unique variance in mathematics scores accounted for by each of the working memory composites. To this end, age, the phonological loop composite, the visuospatial sketchpad composite, and the central executive composite all were entered simultaneously into the model in a first step (Model 1). Thus, the value reported for each of the working memory composites in this model represents the proportion of uniquely explained variance in mathematics achievement after controlling for the influence of the other working memory components and age. In a second step, performance on Raven's matrices was also entered into the model (Model 2) to examine the effect of intellectual ability on the relationships between working memory and mathematics.

The results of the hierarchical regression analysis of first-grade mathematics achievement are presented in Table 4. Model 1 indicates that both the visuospatial sketchpad and central executive composites predicted a significant amount of unique variance in mathematics achievement, whereas the phonological loop composite did not. The results of Model 2 show that the additional incorporation of Raven's matrices into the model did not change the findings of Model 1, although the amount of unique variance explained by the central executive composite decreased.

Table 4
Hierarchical regression analysis of first-grade mathematics achievement.

Variable	Beta	t	Unique R^2
Model 1			
Age	−.08	−0.79	.01
Phonological loop	.10	0.86	.01
Visuospatial sketchpad	.38	3.70***	.12
Central executive	.35	2.90**	.07
$F(4,76) = 11.28^{***}$, $R^2 = .39$			
Model 2			
Age	−.09	−0.94	.00
Phonological loop	.10	0.84	.00
Visuospatial sketchpad	.34	3.20**	.08
Central executive	.26	2.06*	.04
Raven's matrices	.21	1.97*	.03
$F(5,74) = 9.88^{***}$, $R^2 = .42$			

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

The hierarchical regression analysis of second-grade mathematics achievement is presented in Table 5. Model 1 reveals that both the phonological loop and central executive composites made a significant unique contribution to the prediction of second-grade mathematics achievement, whereas the visuospatial sketchpad composite did not. When intellectual ability was also entered into the model (Model 2), only the phonological loop predicted a significant amount of unique variance in second-grade mathematics achievement.

In the next analysis, we predicted second-grade mathematics achievement while controlling for the autoregressive effect of prior mathematical ability, that is, first-grade mathematics achievement. By controlling this effect, it is possible to investigate relations between working memory and later mathematics achievement that were not affected by prior mathematical skills. The results of these regression analyses are shown in Table 6. To find out whether the relationship between a particular working memory composite and second-grade mathematics achievement was affected by first-grade achievement, we first estimated for each working memory composite a separate regression model, thereby controlling for the effects of first-grade mathematics achievement and age (Models 1, 2, and 3). Second, all working memory composites were simultaneously entered into the model together with first-grade mathematics achievement and age to determine the unique contribution of a working memory composite to second-grade mathematics achievement after controlling for the other working memory composites, first-grade mathematics achievement, and age (Model 4). Finally, Raven's matrices were included to examine the additional effect of intellectual ability on the associations between working memory and mathematics achievement (Model 5).

When each of the working memory composites was considered separately (Models 1, 2, and 3), only the phonological loop and the central executive significantly predicted second-grade mathematics achievement when controlling for first-grade mathematics achievement and age. When all working memory composites were simultaneously entered into the model (Model 4), only the phonological loop remained a significant unique predictor of individual differences in mathematics, whereas the effect of the central executive turned insignificant. Thus, unlike the model without controlling for first-grade achievement (Table 5, Model 1), the central executive did not uniquely explain individual differences in second grade that were independent of prior mathematics abilities. These findings remained when also accounting for intellectual ability (Model 5).

Discussion

This study aimed to examine the predictive relationship between working memory and later mathematics achievement in first and second grades by means of a longitudinal correlational design. Therefore, we assessed each working memory component at the beginning of first grade and collected

Table 5
Hierarchical regression analysis of second-grade mathematics achievement.

Variable	Beta	t	Unique R^2
Model 1			
Age	.01	0.10	.00
Phonological loop	.25	2.30*	.04
Visuospatial sketchpad	.18	1.82	.02
Central executive	.36	3.17**	.08
$F(4,82) = 10.41^{***}$, $R^2 = .35$			
Model 2			
Age	−.02	−0.25	.00
Phonological loop	.24	2.43*	.04
Visuospatial sketchpad	.14	1.50	.02
Central executive	.18	1.65	.02
Raven's matrices	.42	4.39***	.15
$F(5,80) = 14.64^{***}$, $R^2 = .49$			

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

Table 6
Hierarchical regression analysis of second-grade mathematics achievement controlling for prior mathematics achievement.

Variable	Beta	t	Unique R^2
Model 1			
Prior mathematics achievement	0.62	7.23***	0.34
Age	0.01	0.07	0
Phonological loop	0.26	3.04**	0.06
$F(3,70) = 26.49^{***}$, $R^2 = .54$			
Model 2			
Prior mathematics achievement	0.66	7.12***	0.41
Age	−.00	−0.02	0
Visuospatial sketchpad	0.09	0.98	0.01
$F(3,70) = 21.20^{***}$, $R^2 = .49$			
Model 3			
Prior mathematics achievement	0.57	6.17***	0.26
Age	0.02	0.2	0
Central executive	0.28	3.06**	0.06
$F(3,70) = 26.58^{***}$, $R^2 = .54$			
Model 4			
Prior mathematics achievement	0.53	5.62***	0.23
Age	−.02	−0.27	0
Phonological loop	0.21	2.08*	0.03
Visuospatial sketchpad	0.12	1.29	0.01
Central executive	0.16	1.54	0.02
$F(5,70) = 17.63^{***}$, $R^2 = .58$			
Model 5			
Prior mathematics achievement	0.44	4.79***	0.15
Age	−.05	−0.60	0
Phonological loop	0.21	2.27*	0.03
Visuospatial sketchpad	0.12	1.36	0.01
Central executive	0.09	0.92	0
Raven's matrices	0.27	2.95**	0.07
$F(4,69) = 19.82^{***}$, $R^2 = .65$			

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

mathematics achievement data 4 months later (in the middle of first grade) and 1 year later (at the start of second grade). The correlational analyses showed that each working memory component was predictively related to mathematics achievement in first and second grades. The regression analyses revealed that the visuospatial sketchpad and the central executive predicted unique variance in first-grade mathematics achievement. With regard to second-grade mathematics achievement, both the phonological loop and the central executive emerged as unique predictors. When also accounting for the influence of first-grade mathematics achievement, only the phonological loop remained a unique predictor.

Before we turn to the associations between working memory and mathematics achievement, the working memory model employed in the current study merits comment. Baddeley's influential three-component model, consisting of the phonological loop, the visuospatial sketchpad, and the central executive (Baddeley, 1986, 2003; Baddeley & Logie, 1999), served as our framework. A confirmatory factor analysis confirmed that this structure fitted our data and revealed that the central executive was highly related to both the phonological loop and the visuospatial sketchpad, whereas the latter two were only weakly interrelated. This correlational pattern does not favor eliminating one of the components as a factor; rather, it reinforces a model of three separate but related components. This is consistent with earlier findings obtained in primary school using similar tasks (Alloway et al., 2006; Gathercole et al., 2004) and with the theoretical claim that the central executive is responsible for coordinating the transmission of information from the slave systems (Baddeley, 1986, 2003; Baddeley & Logie, 1999). Because the measures of the central executive required some form of verbal storage, correlations with the phonological loop can be expected (e.g., Baddeley & Logie, 1999). Associations between measures of the central executive and the visuospatial sketchpad may be found because the latter measures tend to draw on general resources associated with the central executive, particularly at younger ages (e.g., Alloway et al., 2006).

Consistent with previous research (Bull & Scerif, 2001; Gathercole & Pickering, 2000a; Hecht et al., 2001; Holmes & Adams, 2006; Noël et al., 2004; Passolunghi et al., 2007; Swanson & Kim, 2007), our findings provide evidence for a relationship between working memory and mathematics achievement in first and second grades. Most important, our longitudinal correlational design shows that working memory is a precursor of later mathematics achievement, which extends the evidence for a concurrent relationship found in cross-sectional studies. Even at the start of formal schooling, working memory has a strong predictive value for later mathematics achievement; therefore, working memory assessments at an early age can be valuable diagnostic markers of later mathematics achievement.

A key aim of our longitudinal study was to identify which working memory component uniquely predicted later mathematics achievement and whether this pattern changed from first grade to second grade. To this end, all working memory components were investigated simultaneously, and effects of prior mathematics achievement and intellectual ability were also considered.

As expected, the central executive emerged as a significant unique predictor of first- and second-grade mathematics achievement, consistent with previous cross-sectional studies (Bull & Scerif, 2001; Gathercole & Pickering, 2000b; Holmes & Adams, 2006; Swanson & Kim, 2007) and longitudinal studies (Noël et al., 2004; Passolunghi et al., 2007). Our data extend these findings by showing that the influence of the central executive remained when accounting for all working memory components, including the visuospatial sketchpad. When the influence of prior mathematics achievement was further taken into account, the central executive was no longer a unique predictor of second-grade mathematics achievement. This indicates that the central executive did not explain individual differences in second grade that were independent of prior mathematics abilities.

Turning to the influence of the slave systems, the current study shows that the phonological loop is not a unique predictor of first-grade mathematics achievement, in accordance with previous cross-sectional studies (Gathercole & Pickering, 2000b) and longitudinal studies (Passolunghi et al., 2007). In contrast, the phonological loop emerged as a significant unique predictor of second-grade mathematics achievement, consistent with earlier longitudinal findings in second and third graders (Hecht et al., 2001) and cross-sectional data in older children (Holmes & Adams, 2006; McKenzie et al., 2003). This shift in the predictive value of the phonological loop might reflect an increasing reliance on verbally or phonologically coded information during calculation. Rasmussen and Bisanz (2005) showed that from preschool to elementary school, children learn to use verbal labels for quantitative symbols and employ their phonological working memory to store this information temporarily. The increasing importance of phonological processes may also reflect shifts in children's strategy use for solving arithmetic problems. Arithmetic development consists of a shift from finger counting strategies toward more sophisticated verbal counting strategies and fact retrieval (e.g., Siegler, 1996), the latter two of which are assumed to rely on phonological codes (Dehaene, Piazza, Pinel, & Cohen, 2003) and which are supported by the phonological loop (Lee & Kang, 2002). Geary (1993) argued that the concurrent storage of a problem and its answer, carried out by the phonological loop, will contribute to the development of problem–answer associations or arithmetic facts in long-term memory. Thus, good phonological loop skills will lead to stronger problem–answer associations in long-term memory and better arithmetic fact retrieval, and this will positively affect general mathematics performance. Interestingly, Noël and colleagues (2004) showed that high phonological loop ability predicted higher frequencies of verbal counting procedures and fact retrieval and lower frequencies of finger counting, confirming that high phonological loop ability was associated with more mature addition strategies (see also Bull & Johnston, 1997).

The visuospatial sketchpad appears to be important in explaining individual differences in first-grade, but not second-grade, mathematics performance. This fits with cross-sectional studies that point to a role of the visuospatial sketchpad during early stages of mathematical development (Holmes & Adams, 2006; Holmes et al., 2008; McKenzie et al., 2003; Rasmussen & Bisanz, 2005). It extends the available longitudinal studies (Hecht et al., 2001; Noël et al., 2004; Passolunghi et al., 2007), which have underestimated the role of the visuospatial sketchpad in mathematical development.

Holmes and Adams (2006) suggested that the visuospatial sketchpad provides a workspace for representing abstract mathematical knowledge in a concrete form. Rasmussen and Bisanz (2005) showed that preschoolers frequently used concrete representations for doing arithmetic, such as fingers and objects, and that the use of these concrete representations required visuospatial working memory. Consistent with other correlational (Holmes & Adams, 2006; Holmes et al., 2008) and dual-task (McKenzie et al., 2003) studies in children, Rasmussen and Bisanz (2005) showed that the need to represent problems in a more concrete form, and consequently the involvement of the visuospatial sketchpad, decreased across development. Our findings are consistent with this age-related shift given that the visuospatial sketchpad was no longer a significant predictor for second-grade mathematics achievement. Because our data were collected in a longitudinal way, the observed shift in the influence of the visuospatial sketchpad cannot be explained by issues related to sample selection, as is the case for the aforementioned cross-sectional studies.

It should be noted that the visuospatial sketchpad might be fractionated into two subsystems: one for maintaining visual information and one for maintaining spatial information (e.g., Della Sala et al., 1999; Logie & Pearson, 1997). The current study used two tasks to assess the visuospatial sketchpad: Block Recall, which is thought to measure the spatial subsystem, and the Visual Patterns Test, which is known to tap the visual subsystem (e.g., Holmes et al., 2008; Logie & Pearson, 1997). Our analyses revealed that the correlations with mathematics achievement were most prominent for the Block Recall measure. This suggests that it is mainly the spatial component of the visuospatial sketchpad that predicts individual differences in mathematics at this age, consistent with recent findings of Holmes and colleagues (2008).

Taken together, the contributions of the slave systems to individual differences in mathematics change with age and shift from a reliance on the visuospatial system to an increasing reliance on the phonological system. This developmental shift may reflect age-related differences in strategy development going from visuospatial strategies, such as finger counting, to verbal strategies, such as verbal counting and fact retrieval. It should be noted that the dependent measure of our study was a general mathematics achievement test, which does not allow a scrutinized examination of children's strategy use during problem solving. Interestingly, Imbo and Vandierendonck (2007a) combined the dual-task method and the choice/no-choice method to examine the effects of working memory on strategy selection and execution in 10- to 12-year-olds and showed that the central executive was of major importance in children's strategy use. Future research should adopt a similar approach in younger children, such as those in the current sample, to examine the influence of the slave systems on children's strategy use.

What is the effect of intellectual ability on the relations between working memory and mathematics achievement in our sample? Controlling for intellectual ability did not change the associations between working memory and first-grade mathematics achievement. In second grade, a different picture emerged. The central executive was no longer a predictor of mathematics achievement when intellectual ability was incorporated into the model together with all of the working memory components. This suggests that the variance in second-grade mathematics achievement accounted for by the central executive was shared with the variance accounted for by intellectual ability, fitting with the observation that the central executive and intellectual ability are highly related but not identical (Conway, Kane, & Engle, 2003).

When evaluating the results of our study, it is important to note that the conclusions apply only to the specific developmental period under investigation. Moreover, we cannot exclude that the differences between first and second grades reflect differences in the administered mathematics tests. These tests were not the same, and the observed differences might be explained by the fact that the tests assessed different mathematical skills, which would imply different working memory resources. However, the mathematics tests were highly correlated, and the only substantial difference was the number domain involved (0–10 in first grade and 0–20 in second grade) rather than the nature of the mathematical abilities that were tested (both tests covered number knowledge, understanding of operations, arithmetic, word problems, and measurement). Nevertheless, the second-grade test involved more knowledge of the number system, which might be considered as a (symbolic) language. This might explain why the phonological loop, rather than the visuospatial sketchpad, emerged as a better predictor of second-grade mathematics achievement.

Although the longitudinal design of our study provides information regarding the direction of relation between working memory and mathematics achievement, it remains correlational. Therefore, future longitudinal studies should include elements of experimental design, such as the dual-task paradigm, to allow a more direct measurement of the influence of working memory components on mathematics performance.

It remains an open question whether the observed effects of working memory remain when other variables that are related to individual differences in mathematics performance are included. For example, it has been proposed that the ability to understand and represent quantities, typically measured with basic number processing tasks such as number comparison, places important constraints on the development of arithmetic skills (Butterworth, 2005; Dehaene, 1997). Similar to working memory research, most of the work on the role of basic number processing in arithmetic development has focused on atypical performance (De Smedt et al., 2009; Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007), showing that impairments in number comparison are related to the development of mathematical disabilities. Interestingly, there is growing evidence in typically developing children indicating that number comparison is an important predictor of mathematics achievement (Durand, Hulme, Larkin, & Snowling, 2005; Holloway & Ansari, 2009). However, these studies are cross-sectional, and longitudinal work in this area is clearly needed as well. Such studies should also look at the differential contribution of working memory and number processing skills in the prediction of mathematics achievement.

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