Current Psychology
https://doi.org/10.1007/s12144-022-02998-z

How does working memory matter in young children's arithmetic skills: The mediating role of basic number processing

Yue Qi[1,2] · Yinghe Chen[1,2] · Xiujie Yang[1] · Yusi Hao[1]

Accepted: 9 March 2022

Abstract
The current study investigated whether and how each component of the working memory model was associated with kindergarten children's arithmetic performance. A total of 103 Chinese kindergarten children were administered tests of the visuospatial sketchpad, the phonological loop, the central executive, and basic number processing (i.e., number line estimation, nonverbal numerosity estimation and numerical magnitude comparison). The results showed that among the three working memory components, the central executive accounted for a significant proportion of the variance in young children's arithmetic performance. In terms of basic number processing, number line estimation and numerical magnitude comparison had significant influences on young children's arithmetic performance. Furthermore, numerical magnitude comparison played a mediating role between the visuospatial sketchpad and early arithmetic skills. These findings highlight the importance of working memory and basic number processing in early arithmetic skills and reveal different pathways through which the three working memory components influence young children's arithmetic performance.

Keywords Working memory · Basic number processing · Arithmetic · Kindergarten children · Mediating effect

Introduction

The mastery of basic arithmetic skills is considered a key goal in early education (Göbel et al., 2014). Nevertheless, difficulties with calculation are typically recognized late in primary school (Olkun & Denizli, 2015), and children with such difficulties usually also have working memory deficits (Andersson & Lyxell, 2007; D'Amico & Guarnera, 2005). Although working memory has been recognized as a multidimensional concept, little research has considered which of the working memory components truly matter for arithmetic development, especially when children are at young ages. The purpose of the current study is twofold. First, we investigated which of the working memory components are associated with arithmetic development. Second, we examined how these working memory components explain variance in arithmetic ability. Knowing whether and how different working memory components are related to children's arithmetic development could contribute to the identification of children at risk of dyscalculia and is important for efficient instructional design.

Yue Qi and Yinghe Chen contributed equally.

✉ Xiujie Yang
amyyang@bnu.edu.cn

1 Faculty of Psychology, Beijing Normal University, 19 Xinjiekouwai Avenue, Haidian District, 100875 Beijing, People's Republic of China

2 School of Developmental Psychology, Faculty of Psychology, Beijing Normal University, 19 Xinjiekouwai Avenue, Haidian District, 100875 Beijing, People's Republic of China

Working Memory and Arithmetic Skills

The notion that working memory is related to and important for mathematical development has been supported by many studies (see Raghubar et al., 2010 for a review). Working memory is a limited capacity system that enables the temporary storage and manipulation of relevant information in order to accomplish complex cognitive tasks (Baddeley, 2010). The most influential model of working memory is the multicomponent model proposed by Baddeley and Hitch (1974). This model identifies three components of working memory: the visuospatial sketchpad, the phonological loop and the central executive. The visuospatial sketchpad is responsible for the temporary storage of visual spatial information, while the phonological loop is responsible for

Published online: 25 March 2022

the temporary storage of verbal and auditory information. The third component, the central executive, is considered to be the core of working memory. The central executive coordinates the visuospatial sketchpad and the phonological loop and is responsible for inhibiting irrelevant information, shifting attention and updating information. Performing mathematical calculations requires several subprocesses, such as the temporary storage of phonological information, retrieving computation rules from long-term memory, retaining intermediate values and finally outputting the results (DeStefano & LeFevre, 2004). These processes must be supported by the working memory system to temporarily store information while performing mental operations.

There are also many studies that have demonstrated the relationship between working memory and arithmetic skills in children. When focusing on typically developed children, working memory significantly predicts children's arithmetic skills, and the contribution of working memory to arithmetic skills is not eliminated by the presence of other domain-general factors, including chronological age, IQ, processing speed, attention, reading and short-term memory (Berg, 2008; Fuchs et al., 2005). Compared with typically developed children, children with dyscalculia have relatively poor working memories (Andersson & Lyxell, 2007). In addition, working memory training improves arithmetic skills in children with working memory deficits (Bergman-Nutley & Klingberg, 2014).

Longitudinal studies and experimental studies have provided evidence that strengthens our understanding of the causal relationship between working memory and arithmetic skills (Fürst & Hitch, 2000; Hornung et al., 2014; Mckenzie et al., 2003; Xenidou-Dervou et al., 2014; Yang et al., 2019). For example, Hornung et al. (2014) conducted a longitudinal study and found that kindergarten children's working memory, specifically their central executive, significantly predicted their arithmetic ability in first grade. This relationship has also been verified in experimental studies using a dual-task paradigm. Heavy cognitive workloads on the visuospatial sketchpad and phonological loop (Mckenzie et al., 2003), as well as on the central executive (Xenidou-Dervou et al., 2014), significantly impaired children's performance on arithmetic tasks. Further evidence has also revealed that working memory influences different aspects of arithmetic development, such as strategy use (Ai et al., 2017) and understanding of conceptual principles underlying calculation (Cragg et al., 2017).

However, when considering the relationships between the different components of working memory and arithmetic skills, the results are mixed. In general, much evidence suggests that central executive resources are related to children's arithmetic performance (Corso & Dorneles, 2018; Xenidou-Dervou et al., 2014), regardless of the complexity of the question and form of its presentation (Destefano & LeFevre, 2004). A recent meta-analysis of dual-task experiments also found that the load on the central executive resulted in the greatest impairments to arithmetic performance compared with those on the phonological load and visuospatial load (Chen & Bailey, 2021). However, findings on the roles of the visuospatial sketchpad and the phonological loop are less conclusive.

When performing arithmetic calculations, one needs to rely on the phonological loop to encode, maintain and manipulate phonological information. Therefore, the phonological loop is involved in many of the subprocesses of calculation, including counting, arithmetic fact retrieval and maintaining operands and interim results. Studies have shown that phonological memory is correlated with arithmetic development in kindergarten and primary school students both concurrently (Hecht et al., 2001) and longitudinally (Yang & McBride, 2020). However, other studies have reported limited or nonsignificant relations between the phonological loop and arithmetic performance (Corso & Dorneles, 2018; De Rammelaere et al., 2001; Hecht, 2002). For example, Hecht (2002) found that the phonological loop is only involved in calculation when counting strategies are used. When considering different types of arithmetic problems, De Rammelaere et al. (2001) failed to find an effect from the phonological loop in solving either addition or multiplication problems.

It has been suggested that the visuospatial sketchpad acts as a "mental blackboard" upon which material is encoded, retained and manipulated during calculation (Heathcote, 1994). In line with this point of view, researchers have found that the visuospatial sketchpad correlates and predicts a significant amount of the variance in children's arithmetic development (Berg, 2008; Holmes et al., 2008). In contrast, others have failed to find a significant difference in the visuospatial sketchpad between children with high and low arithmetic skills (Bull et al., 1999).

The abovementioned inconsistencies may partly result from differences in participants' ages. Holmes and Adams (2006) found that younger children's mathematics performance, including in mental arithmetic, relies more on the visuospatial sketchpad, while older children's performance relies more on the phonological loop, which was consistent with a previous study (Mckenzie et al., 2003). Given that fewer studies have focused on younger children than on children in primary school and the importance of the early development of calculation skills, the current study investigated the influence of different working memory components on arithmetic development among kindergarten children.

Basic Number Processing and Arithmetic Skills

Recent research has also highlighted the importance of domain-specific factors in predicting arithmetic development (Corso & Dorneles, 2018; Träff, 2013). For example, number processing deficits are considered to represent the core cognitive deficit associated with mathematics disorders (Moll et al., 2015) and are significantly correlated with arithmetic performance according to previous studies (e.g.Siegler & Booth, 2004; Träff, 2013; Zhang et al., 2016). The triple-code model has been used as a theoretical framework to assess the different components of number processing (Dehaene, 1992). According to this model, numbers are represented in three codes: the visual Arabic code, the auditory verbal code and the analogical magnitude code. These different forms of number representation serve different functions, have distinct functional neurological bases, and are related to performance on specific tasks. Visual number representation is involved in recognizing strings of Arabic digits. The verbal representation refers to numerals represented lexically, phonologically and syntactically, much like any other type of word. Finally, the analogical magnitude representation assists in the processing of numerical quantity information, which is analogous to the spatial mapping of numbers on mental number lines.

Children with mathematical difficulties have deficits in all number codes (verbal, visual-verbal and nonverbal) (Moll et al., 2015). In line with this finding, Smedt et al. (2009) investigated the relationship between basic number processing and arithmetic ability in children with genetic disorders who are at high risk for mathematical difficulties. They found that basic number processing directly accounted for those children's poor performance in arithmetic operations and arithmetical strategy use. Additionally, basic number processing tasks such as number comparison tests and mental number line tests can be used as efficient screening tools to identify students at risk of dyscalculia (Olkun & Denizli, 2015).

There is also much evidence to show that three different forms of number processing all have close relationships with arithmetic skills. Visual number representation is often assessed with nonverbal numerosity estimation tasks (Ansari et al., 2007), in which children are shown arrays of dots for short times and are asked to orally report the number of dots. The accuracy of preschoolers' nonverbal numerosity estimation predicts their arithmetic achievement in the first grade (Bartelet et al., 2014). In terms of neural associations, estimating the number of dots and matching that number to digits also elicited overlapping activity with arithmetic operations (Matejko & Ansari, 2019).

Verbal number representation is often assessed with numerical magnitude comparison tasks (Butterworth, 2003) in which children are shown two digits and are required to say which digit represents the larger number. Preschoolers' ability to complete numerical magnitude comparisons significantly predicted their arithmetic skills in the first grade (Bartelet et al., 2014; Kolkman et al., 2013). Additionally, for older children, performance in numerical magnitude comparison tasks is a consistent predictor of arithmetic achievements from the third grade to the sixth grade (Träff, 2013; Zhang et al., 2016).

To assess analogical magnitude representation, number line estimation tasks are often used. In a number line estimation task, children are presented with a horizontal line in which the left position is associated with a smaller number and the right position is associated with a larger number. Children are asked to make number-to-position or position-to-number estimations on this line (Siegler & Booth, 2004). Making an accurate estimation on the number line, which means having a good understanding of the place-value structure of numerical strings, is essential for arithmetic development. A significant correlation has been observed between children's performance in number line estimation tasks and their mathematical abilities (Siegler & Booth, 2004; Träff, 2013), and training in number line estimation has a positive effect on arithmetic ability as well (Obersteiner et al., 2013).

The Hypothesis of the Mediating Effect of Basic Number Processing

Although the relationship between working memory and basic number processing has been investigated in some previous studies, very few studies have considered the relationship between all working memory components and number processing skills at the same time. Here, we assume that different number processing skills might be predicted by different components of working memory.

According to neuroimaging evidence supporting the triple-code model, processing the verbal form of numbers activates the same region as the phonological loop activates. Similarly, there is an overlap between the region that activates during the processing of the visual form of numbers and the region that is important for spatial working memory (Dehaene et al., 2003). Additionally, according to the weak phonological representation hypothesis (Simmons & Singleton, 2010), phonological processing deficits impair mathematics abilities that rely on manipulations of verbal number codes. Evidence from previous research has revealed that the phonological loop is significantly associated with children's performance on numerical magnitude comparison tasks (Yang et al., 2020) and number line estimation tasks (Friso-van den Bos et al., 2014), in which children need to represent and manipulate numbers in verbal form. For a similar reason, it is assumed that the visuospatial sketchpad has a stronger correlation with the processing of numbers in visual forms. Indeed, there is a significant correlation between the visuospatial sketchpad and performance on nonsymbolic dot comparison tasks (Friso-van den Bos et al., 2014). The visuospatial sketchpad also helps with the visualization and representation of quantities in number line tasks (Gunderson et al., 2012).

The central executive is responsible for coordinating the concurrent storage and processing of numerical information, which are involved in a wide variety of number processing tasks. In terms of the relationship between the central executive and basic number processing, studies have found that the central executive is associated with performance on multiple number processing tasks, including nonsymbolic and symbolic number comparisons and number line estimation (Friso-van den Bos et al., 2014). Measures capturing the different functions of the central executive are associated with number processing to different extents. The updating component is particularly important for the development of mathematical skills, while the strength of the correlations between inhibitions and shifting and mathematical performance is much lower (Friso-van den Bos et al., 2013). Overall, the results above indicate that different forms of number processing are predicted by different working memory components and play important roles in arithmetic development.

The Current Study

The purpose of the present study was to investigate the contributions of different working memory components (the visuospatial sketchpad, the phonological loop and the central executive) to arithmetic ability and whether basic number processing skills can account for the association between working memory and arithmetic development. These questions address the cognitive mechanism that underlies the relationship between working memory and arithmetic skills, especially in young children. The results of this study can further improve our understanding of children's difficulties in calculation and help in the development of instructional and intervention programs.

In the current study, an adapted Corsi block task and forward digit span task were used to assess children's visuospatial sketchpad and phonological loop. The central executive was subdivided into inhibition, attention switching and updating, which were assessed with the flanker task, visual search task and backward digit span task, respectively. The basic number processing tasks used in the current study were the nonverbal numerosity estimation task, numerical magnitude comparison task and number line estimation task. In terms of arithmetic ability, children also completed orally presented addition and subtraction questions.

Several hypotheses were proposed and tested in the present study. First, according to the double-deficit hypothesis, both working memory and basic number processing could play important roles in developing mathematical skills. Therefore, it was hypothesized that each of the working memory components and basic number processing could be significantly correlated with children's arithmetic skills. Second, given that the working memory demands of verbal number representation are greater than those of nonverbal numerosity estimation (Destefano & LeFevre, 2004; Yang et al., 2020), it was hypothesized that numerical magnitude comparison and number line estimation would have stronger relations with working memory than nonverbal numerosity estimation and would act as mediators of the relations between the working memory components and arithmetic performance. Third, given that the visuospatial sketchpad is more closely associated with visual spatial information (Baddeley, 2010; Holmes et al., 2008) and that visual-spatial skills are very important in mathematics among young Chinese children (Holmes et al., 2008; Yang et al., 2019), it should have a strong relationship with basic number processing and arithmetic skills. Finally, given that the central executive coordinates the phonological loop and visuospatial sketchpad and is responsible for keeping track of current mental activities (Friso-van den Bos et al., 2013), it was expected to be associated with all the basic number processing subskills.

Method

Participants

A total of 103 children (62 boys and 41 girls, mean age: 63.06 ± 8.70 months) participated in the study. They were recruited from two public kindergartens in Henan (31 boys and 15 girls, mean age: 64.24 ± 10.58 months) and Beijing (31 boys and 26 girls, mean age $= 62.11 \pm 8.70$ months), China. There were no significant differences between the two groups in age ($t = 1.189$, $p = 0.238$) or gender ($\chi^2 = 1.797$, $p = 0.180$). The study was conducted in July and August, 2020. All children were native Mandarin speakers and had normal or corrected-to-normal vision and hearing. The study was approved by the faculty of psychology at the university. The consent obtained from the parents of all research participants was both informed and written prior to testing. According to the national statistics data (National Bureau of Statistics of the People's Republic of China, 2020; State Council of the People's Republic of China, 2020), the average per capita disposable income in Henan is comparable to that of the middle income group, while the average per capita disposable income in Beijing falls between that of the higher-middle income group and higher income group, which reflects that most of the children in our study came from middle and higher-middle SES families, and family SES of children in Beijing was higher than that of children in Henan.

Measures

Phonological Loop We used the forward digit span task to assess the children's phonological loop (Hornung et al., 2014). This task was previously used by Swanson and Kim (2007). In this task, digit sequences were orally presented at a rate of one digit per second, and then the children were instructed to repeat the digits in the same order. The test began with sequences of a three-digit length and progressed to those of a ten-digit length with two sequences for each length. Testing stopped when two sequences of the same length were both repeated incorrectly. The final score was the number of correct trials. The Cronbach's α for this task was 0.84.

Visuospatial Sketchpad The adapted Corsi block task tested the children's ability to remember visual sequences within a matrix (Holmes et al., 2008). In this task, three to nine boxes within a matrix are tapped with a white dot. Children were instructed to indicate where the dot had been and to click on those boxes in the same order as they observed the dot appearing. The final score was the number of correctly recalled positions. The Cronbach's α for this task was 0.82.

Central Executive We used an adapted flanker task (Wei et al., 2012), an adapted visual search task (Cheng et al., 2021) and a backward digit span task (Hornung et al., 2014; Swanson & Kim, 2007) to measure inhibition, attention switching and updating, respectively. The final score for the central executive was calculated as the sum of the standardized scores of these three tasks.

In the adapted flanker task, five arrows or one arrow and four short lines were presented on the screen. The arrow in the middle was the target arrow. Children were asked to judge the direction of the target arrow by pressing "Q" on the keyboard for left and "P" for right. There were three conditions in this task: in the incongruent condition, four arrows were pointed in the direction opposite to the central one; in the congruent condition, all arrows were pointed in the same direction; and in the neutral condition, the target arrow was in the middle of four short lines. There were totally 48 trials in this task. The final score was the number of correct trials minus the number of incorrect trials. The Cronbach's α for this task was 0.91.

In the adapted visual search task, different kinds of figure combinations scrolled across the screen at a constant rate. The target stimulus was the combination of circles and squares. Children were asked to identify and click on the target figure. The task was limited to 4 min. Each correct click on the target figure was recorded as a 1, while a missed target was recorded as a 0 and wrong click was recorded as a -1. The points were then added up to give a final score. The split-half reliability for this task was 0.92.

In the backward digit span task, digit sequences were orally presented at a rate of one digit per second, and children were instructed to repeat the digits in reverse order. The test began with sequences of a two-digit length and progressed to sequences of an eight-digit length with two sequences of each length. Testing stopped when two sequences of the same length were both repeated incorrectly. The final score was the number of correct trials. The Cronbach's α for this task was 0.82.

Number Line Estimation We used a number line estimation task (Siegler & Booth, 2004) to measure children's analogical magnitude representation. There were 20 trials in the task. In each trial, a numeral and a number line ranging from 0 to 1000 were presented on the computer screen. Children had to put the numeral in the right place on the number line by clicking on the line. Then, the position children clicked was transferred to and recorded as the corresponding number on the standard number line. The score of each trial was calculated as $100 - 100 \times \frac{|response-standard\ answer|}{standard\ answer+|response-standard\ answer|}$, in which 'response' refers to the participants' answer and 'standard answer' refers to the correct number (Cui et al., 2020). The final score was the average score of the 20 trials (rounding to a whole number). The Cronbach's α for this task was 0.65.

Nonverbal Numerosity Estimation Task We used a nonverbal numerosity estimation task (Ansari et al., 2007) to assess children's visual number representation. In the nonsymbolic numerosity estimation task, a disk with varying numbers of black dots appeared on the screen for a short time. Children had to estimate the number of black dots after the disk disappeared. There were 27 trials in the task. The final score was calculated following the same rule as was used for the number line estimation task. The Cronbach's α for this task was 0.88.

Numerical Magnitude Comparison Task We used a numerical magnitude comparison task (Butterworth, 2003) to test children's verbal number representation. In the symbolic magnitude comparison task, children were shown pairs of numerals (e.g., 8 and 4) one by one and were asked to decide which numeral in each pair carried a larger numerical quantity by pressing "Q" on the keyboard for the left numeral and "P" for the right one. The task was limited to 2.5 min, and the final score was the number of correct trials minus the number of incorrect trials. The Cronbach's α for this task was 0.98.

Arithmetic Skills The arithmetic task contained 13 addition items and 13 subtraction items (Yang & McBride, 2020). For the addition items, children had to calculate the sum of two numbers that were orally presented. All the items summed to 20 or below based on the children's arithmetic level. For the subtraction items, children had to solve the calculation problem with numbers not greater than 20. There were no time restrictions on obtaining the answers. The items were of increasing difficulty, and the testing of both addition and subtraction stopped after four consecutive failures. The final score was the total number of correct trials. The Cronbach's α for this task was 0.94.

Procedure

The battery of tests was administered during one session lasting approximately 40–50 min with a short break. All but three tests (the forward digit span task, the backward digit span task and the arithmetic task) were administered using a web-based psychological testing system (www.dweipsy.com/lattice), which allowed children's responses to be automatically recorded and sent to a central server via the Internet. For the forward and backward digit span tasks and arithmetic tasks, the items were orally presented to the children, and the children's responses were manually recorded. Children were tested individually online and monitored by trained experimenters through computer screen sharing. They were also accompanied by a teacher or one of their parents during the testing period, and teachers and parents were instructed to remain silent and not to intervene throughout the test. The experimenters provided instructions for each task to the children. For the visuospatial sketchpad test, nonverbal numerosity estimation task, number line estimation task and numerical magnitude comparison task, the children completed practice trials before the formal tests. The practice trials were similar to the formal tests and provided children with feedback. Formal testing did not begin until children finished those practice trials and had no more questions about how to complete the tasks.

Data Analysis

First, the preliminary analyses examined the descriptive statistics and correlations among all study variables. Then, path analysis was used to estimate the mediating role of basic number processing between working memory and arithmetic skills. The model was estimated using Robust Maximum Likelihood estimator (MLR), which allowed all available information to be used (Muthén & Muthén, 2012). All analyses were conducted in SPSS 19.0 and Mplus 7.4.

Results

Preliminary Analyses and Descriptive Statistics

The rates of missing data ranged from 0 to 13.6%, and missing data were due to either technical problems or the children's failure to give an answer. The absolute kurtosis and skewness were below 1.99 and 0.79, respectively. Table 1 shows the range, mean scores, standard deviations, and correlations among all variables in this study. The correlations show that all the components of working memory were significantly correlated with performance on basic number processing tasks and with arithmetic ability. Performance on the three basic number processing tasks was significantly correlated with arithmetic ability. Children's place of residence was significantly associated with all the variables except age and gender. Age was positively associated with the phonological loop, the central executive, nonverbal numerosity estimation, numerical magnitude comparison and arithmetic ability, while gender was only significantly associated with the central executive.

Path Analysis

We first examined the extent to which different working memory components and performance on different basic number processing are associated with children's arithmetic skills via two fully saturated path analysis models. Since this type of model always produces a perfect fit to the data, the model fit indices were not examined, nor are they reported. Age, gender and children's place of residence were statistically controlled for. Regarding the relationship between working memory and arithmetic skills, Fig. 1 shows the standardized estimates for each path. The amount of the variance in the children's arithmetic skills accounted for by the working memory components and control variables was 46% ($p < 0.001$). Age significantly predicted children's arithmetic skills ($\beta = 0.35$, $p < 0.001$). Among the three working memory components, only the central executive served as a significant predictor of arithmetic skills ($\beta = 0.46$, $p = 0.001$). Turning to the relationship between basic number processing and arithmetic skills, Fig. 2 shows the standardized estimates for each path. This model accounted for 52% of the variance in arithmetic skills ($p < 0.001$). Age also had an effect on the children's arithmetic skills ($\beta = 0.32$, $p = 0.002$). Both number line estimation ($\beta = 0.31$, $p = 0.005$) and numerical magnitude comparison ($\beta = 0.38$, $p < 0.001$) explained unique variance in arithmetic skills.

Then, we conducted a mediation analysis to determine whether basic number processing mediated the relationships between the different components of working memory and arithmetic skills after considering age, gender and children's place of residence. We also specified a fully saturated model. Figure 3 presents the standardized estimates for each path. Performance

Table 1 The range, mean scores, standard deviations, and correlations among all variables

	Range	*M*	*SD*	1	2	3	4	5	6	7	8	9	10
1. Age	45 – 90	63.06	8.70	1									
2. Gender [a]	0 – 1	–	0.49	-0.02	1								
3. Place of Residence [b]	0 – 1	–	0.50	-0.12	-0.13	1							
4. Visuospatial Sketchpad	0 – 19	6.03	4.59	0.17	-0.05	0.45***	1						
5. Phonological Loop	0 – 10	3.93	2.83	0.28**	-0.16	0.55***	0.38***	1					
6. Central Executive	-4.97 – 3.97	-0.17	2.13	0.27*	-0.24*	0.66***	0.53***	0.71***	1				
7. Number Line Estimation	41 – 91	66.44	10.46	0.18	0.07	0.62***	0.49***	0.42***	0.47***	1			
8. Nonverbal Numerosity Estimation	50 – 84	65.62	8.99	0.30**	-0.07	0.71***	0.53***	0.64***	0.61***	0.68***	1		
9. Numerical Magnitude Comparison	-15 – 59	24.18	19.85	0.57***	-0.11	0.30**	0.48***	0.53***	0.57***	0.39***	0.53***	1	
10. Arithmetic	0 – 26	8.86	7.10	0.50***	-0.06	0.28**	0.32**	0.50***	0.56**	0.45***	0.51***	0.65***	1

Ns = 89–103. [a] Dummy coded: 0 = boys, 1 = girls. [b] Dummy coded: 0 = Henan, 1 = Beijing

* *p* <.05, ** *p* <.01, *** *p* <.001, *two-tailed*

on the number line estimation ($\beta = 0.29$, $p = 0.005$) and numerical magnitude comparison ($\beta = 0.35$, $p < 0.001$) tasks significantly predicted children's arithmetic ability, while performance on nonverbal numerosity estimation ($\beta = -0.03$, $p = 0.835$) did not. For the relationship between working memory and basic number processing, only the visuospatial sketchpad served as a significant predictor of performance on the numerical magnitude comparison task ($\beta = 0.24$, $p = 0.002$).

Additionally, children in Beijing performed better in the number line estimation ($\beta = 0.43$, $p = 0.001$) and nonverbal numerosity estimation ($\beta = 0.60$, $p < 0.001$) tasks than children in Henan. Additionally, older children outperformed their younger counterparts in numerical magnitude comparisons ($\beta = 0.43$, $p < 0.001$), nonverbal numerosity estimation ($\beta = 0.26$, $p = 0.002$) and arithmetic skills ($\beta = 0.23$, $p = 0.02$).

Table 2 shows the direct and indirect effects of the components of working memory on arithmetic ability. R_M ($R_M = \left|\frac{ab}{c'}\right|$) was calculated and reported to estimate the mediation effect size (Sobel, 1982). Tests of the mediation model showed that the visuospatial sketchpad was indirectly related to arithmetic ability via performance on the numerical magnitude comparison task ($\beta = 0.08$, $p = 0.028$), with mediation effect size $R_M = 0.49$. The direct effect of the central executive was significant ($\beta = 0.36$, $p = 0.005$), and the direct effect of the visuospatial sketchpad was also marginally significant ($\beta = -0.17$, $p = 0.092$). No other significant direct or indirect effects were found. Overall, the mediation model explained 58% of the variance in children's arithmetic performance.

Discussion

The primary purpose of the current study was to investigate the relationships between three working memory components and children's arithmetic skills. The results showed that working memory, basic number processing and early arithmetic skills were significantly associated, and both working memory and basic number processing explained unique variance in arithmetic ability after statistically controlling for age, gender and children's place of residence. We also found that basic number processing played a mediating role between working memory and young children's arithmetic skills. Specifically, performance on the numerical magnitude comparison task significantly mediated the relationship between the visuospatial sketchpad and arithmetic skills.

Among the working memory components, the central executive was significantly associated with early arithmetic.

Fig. 1 The multiple regression model predicting arithmetic ability from the visuospatial sketchpad, the phonological loop and the central executive. $N = 103$. Age, gender and children's place of residence were control variables. All the coefficients are standardized estimates. Black solid lines indicate significant paths, and gray dotted lines indicate nonsignificant paths. * *p* < .05, ** *p* < .01, *** *p* < .001

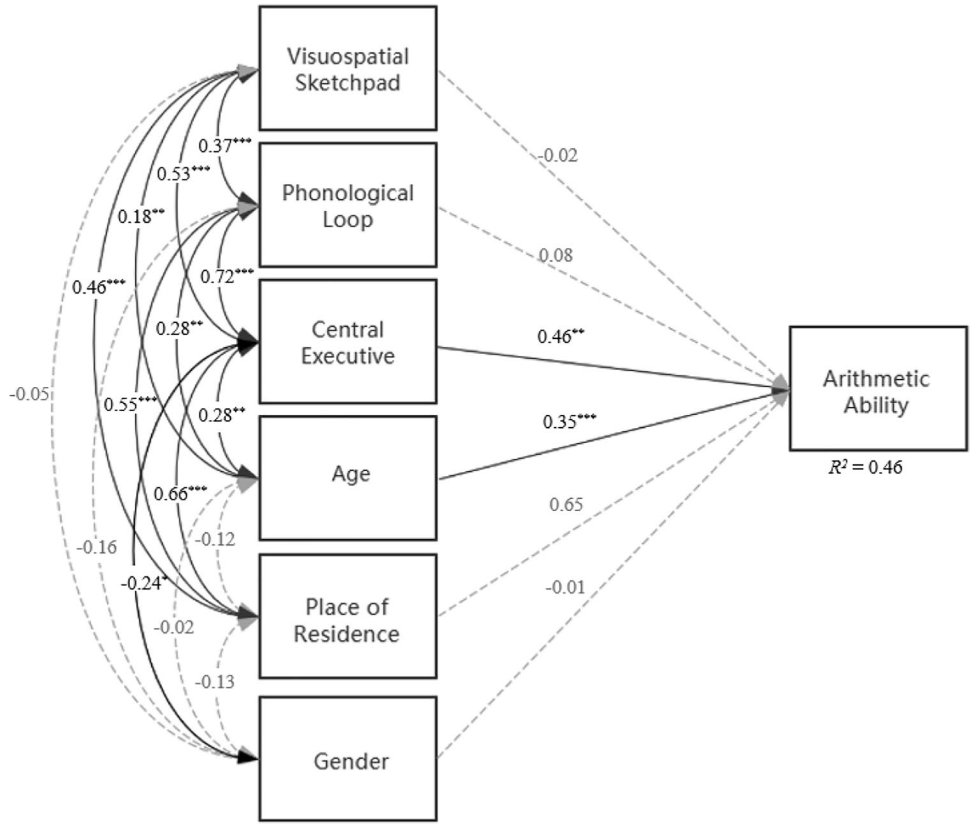
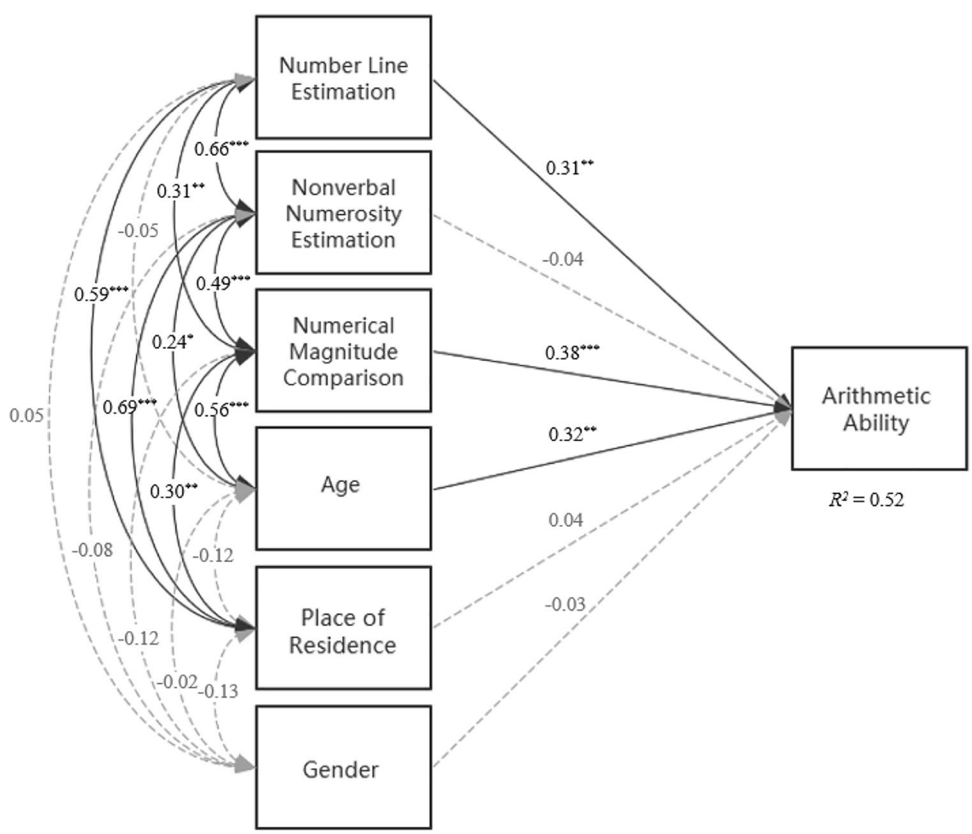


Fig. 2 The multiple regression model predicting arithmetic ability from number line estimation, nonverbal numerosity estimation and numerical magnitude comparison. $N = 103$. Age, gender and children's place of residence were control variables. All the coefficients are standardized estimates. Black solid lines indicate significant paths, and gray dotted lines indicate nonsignificant paths. * *p* < .05, ** *p* < .01, *** *p* < .001



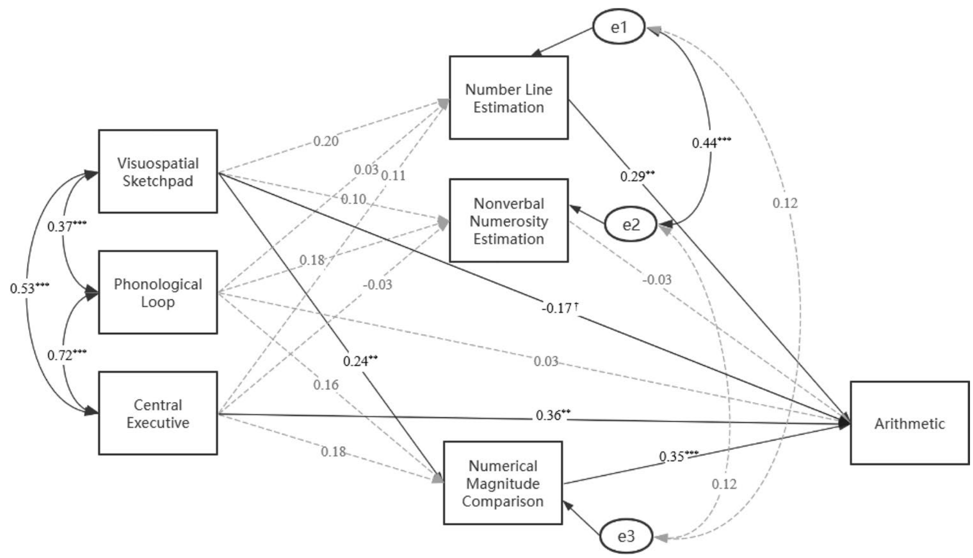


Fig. 3 The mediation model predicting arithmetic from visuospatial sketchpad, phonological loop and central executive. $N = 103$. None of the control variables, including age, gender and place of residence, are shown. All the coefficients are standardized estimates. Black solid lines indicate significant paths, and gray dotted lines indicate nonsignificant paths. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Table 2 Direct and indirect effects from the mediation model with the components of working memory as predictors, basic number processing skills as mediators, and arithmetic skill as the outcome variables

	Coef. (S.E.)	*p (two-tailed)*	*Stand. (S.E.)*	*p (two-tailed)*	*Effect size*
Visuospatial Sketchpad					
Direct Effect	**-0.27(0.15)** †	**.08**	**-0.17(0.10)** †	**.09**	
Total Indirect Effect	**0.21(0.08)** **	**.01**	**0.14(0.05)** **	**.01**	
Visuospatial Sketchpad → Number Line Estimation → Arithmetic	0.09(0.06)	.13	0.06(0.04)	.12	0.34
Visuospatial Sketchpad → Nonverbal Numerosity Estimation → Arithmetic	-0.01(0.03)	.84	-0.003(0.02)	.84	0.02
Visuospatial Sketchpad → Numerical Magnitude Comparison → Arithmetic	**0.13(0.06)** *	**.03**	**0.08(0.04)** *	**.03**	**0.49**
Phonological Loop					
Direct Effect	0.07(0.27)	.80	0.03(0.10)	.80	
Total Indirect Effect	0.15(0.17)	.38	0.06(0.07)	.38	
Phonological Loop → Number Line Estimation → Arithmetic	0.03(0.12)	.83	0.01(0.05)	.83	0.37
Phonological Loop → Nonverbal Numerosity Estimation → Arithmetic	-0.01(0.07)	.83	-0.01(0.03)	.83	0.22
Phonological Loop → Numerical Magnitude Comparison → Arithmetic	0.14(0.10)	.17	0.05(0.04)	.17	2.00
Central Executive					
Direct Effect	**1.17(0.43)** **	**.006**	**0.36(0.10)** **	**.005**	
Total Indirect Effect	0.32(0.23)	.16	0.10(0.07)	.16	
Central Executive → Number Line Estimation → Arithmetic	0.11(0.16)	.49	0.03(0.05)	.49	0.09
Central Executive → Nonverbal Numerosity Estimation → Arithmetic	0.003(0.02)	.88	0.001(0.005)	.88	0.003
Central Executive → Numerical Magnitude Comparison → Arithmetic	0.21(0.16)	.20	0.06(0.05)	.20	0.18

$N = 103$. *Coef.* = estimate of unstandardized path coefficient; *Stand.* = estimate of standardized path coefficient. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

R_M was used as the mediation effect size indicator (R_M=|ab/c'|), the bold entries are the significant effects

This result is in line with those of many previous studies (Corso & Dorneles, 2018; Fürst & Hitch, 2000; Xenidou-Dervou et al., 2014). The central executive is responsible for monitoring and coordinating different steps when solving arithmetic problems and is especially important for complex steps, such as carrying and borrowing operations (DeStefano & LeFevre, 2004). Moreover, the central executive may also influence children's arithmetic performance through the processes of strategy choice and execution (Ai et al., 2017).

In terms of basic number processing, we found that performance on both the number line estimation task and the numerical magnitude comparison task explained unique variance in early arithmetic skills, while performance on the nonverbal numerosity estimation task did not. The nonverbal numerosity estimation task in our study was similar to tasks that measured approximate number sense or nonsymbolic number representation in previous research. In a longitudinal study with 6- to 7-year-old children, Göbel (2014) investigated the role of approximate number sense and knowledge of Arabic numerals in arithmetic development. The results showed that Arabic number knowledge, which was closely related to number line estimation and numerical magnitude comparison performance, served as a powerful predictor of early arithmetic skills. In contrast, approximate number sense did not play an additional role in predicting children's arithmetic skills. Another study showed that performance on symbolic number line estimation tasks and symbolic comparison tasks significantly predicted children's arithmetic skills (including simple addition and subtraction), whereas nonsymbolic tasks did not (Kolkman et al., 2013). Additionally, this result may also be partly explained by the form in which the calculation task was presented. In the current study, arithmetic questions were presented to children orally, so the verbal number processing system as well as analogical magnitude representation might be more important in solving this kind of problem (Simmons & Singleton, 2010). In future studies, the inclusion of comprehensive measures of children's arithmetic skills is recommended to further examine the relationships between basic number processing and different types of calculations.

Furthermore, our study was also concerned with whether and which kind of basic number processing may mediate the relationships between the different working memory components and early arithmetic. Regarding this goal, we found that performance on the numerical magnitude comparison task explained the relationship between the visuospatial sketchpad and arithmetic skills. Although we did not expect a relation between the visuospatial sketchpad and numerical magnitude comparison, the result seems reasonable due to the visual presentation of digits in this task. To make a comparison between visually displayed digits, children should first extract visual information about the digit pairs, maintain this visual information and retrieve the visual digit knowledge for later comparison. Previous studies have also shown that processing symbolic numbers requires the involvement of the visual system (Lefevre et al., 2010; Zhang et al., 2016). In other words, the numerical magnitude comparison task in our study did not merely assess the verbal number processing system but also tapped into the ability to visually represent and store numerical information. Therefore, performance on the numerical magnitude comparison task was closely related to visuospatial sketchpad and mediated the relationship between the visuospatial sketchpad and arithmetic skills. Compared with that of numerical magnitude comparisons, the role of number line estimation and nonverbal numerosity estimation in the relation between visuospatial sketchpad and arithmetic skills was very limited. One possible reason is that the present study only used simple addition and subtraction to measure children's arithmetic skills. Children could solve these arithmetic problems in procedural ways (Holmes & Adams, 2006), regardless of how accurate their numerosity estimation was or whether they had acquired a linear spatial representation of numbers. Understanding the meaning of numerals and gaining the ability to manipulate and compare numbers, by contrast, might be more important for solving simple arithmetic problems.

Although the direct effect of the central executive on arithmetic skills was significant, indicating that the central executive did have an important influence on early arithmetic skills, it probably did not occur via these basic number processing skills. The central executive may play a key role in more complex numerical skills and skills that are more closely associated with arithmetic performance, such as procedural skills or arithmetic fact retrieval (Cragg et al., 2017). Alternatively, the central executive was associated with counting skills (Hecht, 2002) and rapid automatized naming (Fung, 2015), both of which are very important for children's arithmetic skill acquisition (Cui et al., 2017). Future studies should examine whether the relationships between the central executive and arithmetic skills are mediated by other factors, such as counting skill and rapid naming.

Unexpectedly, the present study did not find a significant influence of the phonological loop on early arithmetic skills. This was in contrast with the results in many previous studies (Ding et al., 2019; D'Amico & Guarnera, 2005; Hecht et al., 2001). There are two possible explanations. First, some studies have revealed that children rely more on the visuospatial sketchpad and visual number representation when solving arithmetic problems before the age of seven (Mckenzie et al., 2003; Raghubar et al., 2010). Young children have not yet mastered symbolic number representation and symbolic-linguistic arithmetic and have made less use of mature arithmetic strategies such as fact retrieval (Holmes & Adams, 2006). Indeed, the present results revealed that the visuospatial sketchpad contributed more to kindergarten children's arithmetic development than the phonological loop, which is important for fact retrieval. Second, the numerical magnitude comparison task not only assessed verbal number representation abilities but also indicated the child's ability to distinguish visual number magnitudes. This might overlap with the relationship between the phonological loop and the verbal number processing system. Future studies could make use of tasks that index purely the children's verbal number representation abilities, such as tasks that contain auditory number inputs (Libertus et al., 2020), to re-examine the influence of the phonological loop on basic number processing and arithmetic skills.

There are several limitations to the present study. First, the number line estimation task had low reliability in our study. One possible reason is that this 0–1000 version of the number line estimation task was too difficult for kindergarten children. In future studies, easier tasks (e.g., Obersteiner et al., 2013) with higher reliability could be used to better examine analogical magnitude representation. Second, the sample size should have been larger to distinguish among the effects of the three components of working memory and to test the mediation effects of three different kinds of basic number processing. Finally, children in this study were recruited from two separate regions. Although these two groups of children were matched on age and gender, there were significant differences in their performance on all cognitive tasks. Thus, these differences between the two groups of children may, to some extent, have weakened the strength of the associations among working memory, basic number processing and arithmetic skills. Future studies should include young children who come from similar backgrounds to further examine the relations between working memory, basic number processing and early arithmetic skills.

Despite these limitations, our findings revealed the relative contributions of different working memory components to young children's arithmetic skills and how each working memory component was associated with early arithmetic skills. The results highlight the important role of working memory, especially those of the visuospatial sketchpad and the central executive, in early arithmetic development. In practice, standardized working memory assessments could be used to identify children who are at risk of dyscalculia, starting as early as their preschool years. Training programs for working memory could be developed and conducted to help young children gain various basic number processing skills as well as arithmetic skills and other complex mathematical skills. Since the current study investigated the relationship of interest within a cross-sectional design, it is also important for future studies to examine whether training for working memory could improve basic number processing and early arithmetic skills. Importantly, the present findings reveal that number knowledge, such as understanding the meaning of numerals and remembering their numerical order, contributes greatly to arithmetic development. Children can be encouraged to practice counting, comparing and manipulating numbers ahead to help them understand and acquire addition and subtraction skills at a later time.

Funding This study was funded by the National Natural Science Foundation of China (32000757) to Xiujie Yang, the Science Foundation for the Excellent Youth Scholars from Faculty of Psychology, Beijing Normal University (2019004) to Xiujie Yang, Open Research Fund of the State Key Laboratory of Cognitive Neuroscience and Learning (CNLZD2105) to Xiujie Yang, the National Natural Science Foundation of China (32171061) to Yinghe Chen.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical Statement The study was approved by the ethics committee the faculty of psychology at the university.

Informed Consent In accordance with the Declaration of Helsinki, the consent written prior to testing was informed and obtained from the parents of all research participants.

References

Ai, J., Yang, J., Zhang, T., Si, J., & Liu, Y. (2017). The effect of central executive load on fourth and sixth graders' use of arithmetic strategies. *Psychologica Belgica, 57*(2), 154–172. https://doi.org/10.5334/pb.360

Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: a general or specific deficit? *Journal of Experimental Child Psychology, 96*(3), 197–228. https://doi.org/10.1016/j.jecp.2006.10.001

Ansari, D., Donlan, C., & Karmiloff-Smith, A. (2007). Typical and atypical development of visual estimation abilities. *Cortex, 43*(6), 758–768. https://doi.org/10.1016/S0010-9452(08)70504-5

Baddeley, A. (2010). Working memory. *Current Biology, 20*(4), 136–140. https://doi.org/10.1016/j.cub.2009.12.014

Baddeley, A., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–90). Academic Press.

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2014). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of Experimental Child Psychology, 117*, 12–28. https://doi.org/10.1016/j.jecp.2013.08.010

Berg, D. H. (2008). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology, 99*(4), 288–308. https://doi.org/10.1016/j.jecp.2007.12.002

Bergman-Nutley, S., & Klingberg, T. (2014). Effect of working memory training on working memory, arithmetic and following instructions. *Psychological Research, 78*(6), 869–877. https://doi.org/10.1007/s00426-014-0614-0

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15*(3), 421–442. https://doi.org/10.1080/87565649909540759

Butterworth, B. (2003). *Dyscalculia screener*. London: nferNelson.

Chen, E. H., & Bailey, D. H. (2021). Dual-task studies of working memory and arithmetic performance: A meta-analysis. *Journal of Experimental Psychology: Learning Memory and Cognition, 47*(2), 220–233. https://doi.org/10.1037/xlm0000822

Cheng, D., Ma, M., Hu, Y., & Zhou, X. (2021). Chinese kindergarteners skilled in mental abacus have advantages in spatial processing and attention. *Cognitive Development, 58*, 101046. https://doi.org/10.1016/j.cogdev.2021.101046

Corso, L. V., & Dorneles, B. V. (2018). Working memory, number sense, and arithmetical performance. *Psicologia Teoria E Prática, 20*(1), 155–167. https://doi.org/10.5935/19806906/psicologia.v20n1p155-167

Cragg, L., Keeble, S., Richardson, S., Roome, H. E., & Gilmore, C. (2017). Direct and indirect influences of executive functions on mathematics achievement. *Cognition, 162*, 12–26. https://doi.org/10.1016/j.cognition.2017.01.014

Cui, J., Georgiou, G. K., Zhang, Y., Li, Y., Shu, H., & Zhou, X. (2017). Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children. *Journal of Experimental Child Psychology, 154*, 146–163. https://doi.org/10.1016/j.jecp.2016.10.008

Cui, J. X., Xiao, R., Ma, M., Yuan, L., Cohen Kodash, R., & Zhou, X. (2020). Children skilled in mental abacus show enhanced non-symbolic number sense. *Current Psychology*. Advance online publication. https://doi.org/10.1007/s12144-020-00717-0

D'Amico, A., & Guarnera, M. (2005). Exploring working memory in children with low arithmetical achievement. *Learning & Individual Differences, 15*(3), 189–202. https://doi.org/10.1016/j.lindif.2005.01.002

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and central executive involved? *Memory and Cognition, 29*, 267–273. https://doi.org/10.3758/BF03194920

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3–6), 487–506. https://doi.org/10.1080/02643290244000239

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*(1), 1–42. 10. 1016/0010–0277(92)90049-N

DeStefano, D., & LeFevre, J.-A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology, 16*(3), 353–386. https://doi.org/10.1080/09541440244000328

Friso-van den Bos, I., van der Ven, S. H. G., Kroesbergen, E. H., & van Luit, J. E. H. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review, 10*, 29–44. https://doi.org/10.1016/j.edurev.2013.05.003

Friso-van den Bos, I., Kroesbergen, E. H., & Van Luit, J. E. H. (2014). Number sense in kindergarten children: Factor structure and working memory predictors. *Learning & Individual Differences, 33*, 23–29. https://doi.org/10.1016/j.lindif.2014.05.003

Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., & Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *Journal of Educational Psychology, 97*, 493–513. https://doi.org/10.1037/0022-0663.97.3.493

Fung, W. Y. (2015). *Working memory components as predictors of word problem solving: does rapid automatized naming speed mediate the relationship?* (Doctor Dissertations). University of California.

Fürst, A. J., & Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory & Cognition, 28*(5), 774–782. https://doi.org/10.3758/BF03198412

Göbel, S. M., Watson, S. E., Lervag, A., & Hulme, C. (2014). Children's arithmetic development: It is number knowledge, not the approximate number sense, that counts. *Psychological Science, 25*(3), Article 789. https://doi.org/10.1177/0956797613516471

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental Psychology, 48*(5), 1229–1241. https://doi.org/10.1037/a0027433

Heathcote, D. (1994). The role of visuo-spatial working memory in the mental addition of multi-digit addends. *Current Psychology of Cognition, 13*, 207–245. https://doi.org/10.1006/brln.1994.1027

Hecht, S. A. (2002). Counting on working memory in simple arithmetic when counting is used for problem solving. *Memory & Cognition, 30*(3), 447–455. https://doi.org/10.3758/BF03194945

Hecht, S. A., Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *Journal of Experimental Child Psychology, 79*(2), 192–227. https://doi.org/10.1006/jecp.2000.2586

Holmes, J., & Adams, J. W. (2006). Working memory and children's mathematical skills: Implications for mathematical development and mathematics curricula. *Educational Psychology, 26*(3), 339–366. https://doi.org/10.1080/01443410500341056

Holmes, J., Adams, J. W., & Hamilton, C. J. (2008). The relationship between visuospatial sketchpad capacity and children's mathematical skills. *European Journal of Cognitive Psychology, 20*(2), 272–289. https://doi.org/10.1080/09541440701612702

Hornung, C., Schiltz, C., Brunner, M., & Martin, R. (2014). Predicting first-grade mathematics achievement: the contributions of domain-general cognitive abilities, nonverbal number sense, and early number competence. *Frontiers in Psychology, 5*, Article 272. https://doi.org/10.3389/fpsyg.2014.00272

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. M. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and Instruction, 25*(2), 95–103. https://doi.org/10.1016/j.learninstruc.2012.12.001

Lefevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development, 81*(6), 1753–1767. https://doi.org/10.1111/j.1467-8624.2010.01508.x

Libertus, M. E., Odic, D., Feigenson, L., & Halberda, J. (2020). Effects of visual training of approximate number sense on auditory number sense and school math ability. *Frontiers in Psychology, 11*, Article 2085. https://doi.org/10.3389/fpsyg.2020.02085

Matejko, A. A., & Ansari, D. (2019). The neural association between arithmetic and basic numerical processing depends on arithmetic problem size and not chronological age. *Developmental Cognitive Neuroscience, 37*, Article 100653. https://doi.org/10.1016/j.dcn.2019.100653

Mckenzie, B., Bull, R., & Gray, C. (2003). The effects of phonological and visual-spatial interference on children's arithmetical performance. *Educational & Child Psychology, 20*(3), 93–108. https://doi.org/10.1037/0022-0663.98.1.29

Moll, K., Göbel, S. M., & Snowling, M. J. (2015). Basic number processing in children with specific learning disorders: Comorbidity of reading and mathematics disorders. *Child Neuropsychology, 21*(3), 399–417. https://doi.org/10.1080/09297049.2014.899570

Muthén, L. K., & Muthén, B. O. (2012). *Mplus user's guide* (7th ed.). Muthén & Muthén.

National Bureau of Statistics of the People's Republic of China. (2020). *Annual by Province: People's living conditions.* Retrieved November 1, 2021, from https://data.stats.gov.cn/english/easyquery.htm?cn=E0103
Obersteiner, A., Reiss, K., & Ufer, S. (2013). How training on exact or approximate mental representations of number can enhance first-grade students' basic number processing and arithmetic skills. *Learning & Instruction, 23*, 125–135. https://doi.org/10.1016/j.learninstruc.2012.08.004
Olkun, S., & Denizli, Z. A. (2015). Using basic number processing tasks in determining students with mathematics disorder risk. *Düşünen Adam Journal of Psychiatry & Neurological Sciences, 28*(1), 47–57. https://doi.org/10.5350/DAJPN2015280105
Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning & Individual Differences, 20*(2), 110–122. https://doi.org/10.1016/j.lindif.2009.10.005
Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development, 75*(2), 428–444. https://doi.org/10.1111/j.1467-8624.2004.00684.x
Simmons, F. R., & Singleton, C. (2010). Do weak phonological representations impact on arithmetic development? a review of research into arithmetic and dyslexia. *Dyslexia, 14*(2), 77–94. https://doi.org/10.1002/dys.341
Smedt, B. D., Reynvoet, B., Swillen, A., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Basic number processing and difficulties in single-digit arithmetic: Evidence from velo-cardio-facial syndrome. *Cortex, 45*(2), 177–188. https://doi.org/10.1016/j.cortex.2007.06.003
Sobel, M. E. (1982). Asymptotic confidence intervals for indirect effects in structural equation models. In S. Leinhardt (Ed.), *Sociological methodology 1982* (pp. 290–312). American Sociological Association.
State Council of the People's Republic of China. (2020). *National per capita disposable income by 2020*. Retrieved November 1, 2021, from http://www.gov.cn/guoqing/202104/09/content_559866 2.htm
Swanson, & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence, 35*(2), 151–168. https://doi.org/10.1016/j.intell.2006.07.001
Träff, U. (2013). The contribution of general cognitive abilities and number abilities to different aspects of mathematics in children. *Journal of Experimental Child Psychology, 116*(2), 139–156. https://doi.org/10.1016/j.jecp.2013.04.007
Wei, W., Yuan, H., Chen, C., & Zhou, X. (2012). Cognitive correlates of performance in advanced mathematics: Cognitive correlates of advanced mathematics. *British Journal of Educational Psychology, 82*(1), 157–181. https://doi.org/10.1111/j.2044-8279.2011.02049.x
Xenidou-Dervou, I., van Lieshout, E. C. D. M., & Schoot, M. V. D. (2014). Working memory in nonsymbolic approximate arithmetic processing: A dual-task study with preschoolers. *Cognitive Science, 38*(1), 101–127. https://doi.org/10.1111/cogs.12053
Yang, X., & McBride, C. (2020). How do phonological processing abilities contribute to early Chinese reading and mathematics? *Educational Psychology, 40*(7), 893–911. https://doi.org/10.1080/01443410.2020.1771679
Yang, X., Chung, K. K. H., & Mcbride, C. (2019). Longitudinal contributions of executive functioning and visual-spatial skills to mathematics learning in young Chinese children. *Educational Psychology, 39*(5), 678–704. https://doi.org/10.1080/01443410.2018.1546831
Yang, X., Zhang, X., Huo, S., & Zhang, Y. (2020). Differential contributions of cognitive precursors to symbolic versus non-symbolic numeracy in young Chinese children. *Early Childhood Research Quarterly, 53*, 208–216. https://doi.org/10.1016/j.ecresq.2020.04.003
Zhang, Y., Chen, C., Liu, H., Cui, J., & Zhou, X. (2016). Both non-symbolic and symbolic quantity processing are important for arithmetical computation but not for mathematical reasoning. *Journal of Cognitive Psychology, 28*(7), 807–824. https://doi.org/10.1080/20445911.2016.1205074