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Does numerical processing uniquely predict first graders' future development of single-digit arithmetic? ☆

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ABSTRACT

The present longitudinal study investigated whether children's numerical processing skills at the start of formal schooling predict subsequent development in single-digit arithmetic and fact retrieval. At the start of first grade, we administered measures of numerical processing (digit naming, symbolic numerical magnitude comparison, nonsymbolic numerical magnitude comparison) as well as measures of intellectual ability, preschool mathematical abilities, working memory and processing speed. Our longitudinal data indicate that children's numerical processing skills at primary school entrance were predictively related to their future competence in single-digit arithmetic and their reliance on arithmetic fact retrieval. This association was not explained by children's intellectual ability, preschool mathematical abilities, verbal working memory, visual-spatial short-term memory and processing speed. These findings indicate that numerical processing skills precede children's development in single-digit arithmetic.

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There is converging evidence that links proficient numerical processing skills, with higher mathematics achievement (De Smedt, Noël, Gilmore, & Ansari, 2013) but this knowledge is largely based on cross-sectional data. Such findings do not allow us to conclude whether numerical processing is a precursor of mathematics achievement. Only but a few longitudinal studies are currently available. These studies have reported consistent and predictive associations between symbolic numerical magnitude comparison (i.e. comparing Arabic digits) and children's future general mathematics achievement (e.g., De Smedt, Verschaffel, & Ghesquière, 2009; Sasanguie, Van den Bussche, & Reynvoet, 2012). Conflicting findings have been reported for the nonsymbolic numerical magnitude comparison (i.e. comparing dot arrays). While some studies observed that nonsymbolic magnitude comparison predict future general mathematics achievement (Libertus, Feigenson, & Halberda, 2013a,b; Mazzocco, Feigenson, & Halberda, 2011), others have failed to find such longitudinal association (Sasanguie et al., 2012). One possible explanation for this might be that the abovementioned studies investigated mathematical competence with broad general standardized mathematics achievement tests. These tests reflect performance averaged across various mathematical skills and it has been observed that numerical processing impacts more on some specific mathematical skills compared to others. For example,

Linsen, Verschaffel, Reynvoet, and De Smedt (2014) showed that in multi-digit subtraction, the use of the flexible subtraction-by-addition strategy relied more on numerical processing than the more common direct subtraction strategy (see also Fuchs, Geary, Fuchs, Compton, & Hamlett, 2014; Jordan, Mulhern, & Wylie, 2009).

Three longitudinal studies focused on one specific mathematical skill, i.e. arithmetic, and investigated how numerical processing predicted subsequent performance (Bartelet, Vaessen, Blomert, & Ansari, 2014; Desoete, Ceulemans, De Weerd, & Pieters, 2010; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). Desoete et al. (2010) found that nonsymbolic numerical magnitude comparison accuracy in preschool predicted arithmetic in first and second grade, independently of intellectual ability. Bartelet et al. (2014), however, demonstrated that preschool symbolic, but not nonsymbolic numerical magnitude comparison predicted first graders arithmetic, even when controlling for gender, intelligence and processing speed. Sasanguie et al. (2013) reported that the speed of comparing Arabic digits in the middle of first grade predicted arithmetic one year later, even after controlling for spelling achievement.

One limitation of these three longitudinal studies is that they did not account for children's mathematical abilities when they enter formal schooling. This is important because children have a good deal of mathematical knowledge before they receive formal mathematics instruction (Barth, Beckmann, & Spelke, 2008; Resnick, 1989). For example, children intuitively learn from a very young age concepts such as absolute size (e.g., small, big) or part-whole relations and these early mathematical abilities emerge as reliable predictors of children's subsequent growth in mathematics (e.g., Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). A meta-analysis by Duncan et al. (2007) even pointed out that school-entry mathematical competence was the strongest predictor of

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children's future academic performance. Taking into account these pre-school mathematical abilities will allow us to investigate whether there is a unique and robust predictive association between numerical processing at the onset of formal schooling and future competence in single-digit arithmetic, which was the aim of the current study.

The present study focuses on single-digit arithmetic up to 10. This is because arithmetic comprises a major objective in the first grades of mathematics education and constitutes a building block for subsequent growth in mathematics (Kilpatrick, Swafford, & Findell, 2001). Various studies have described how children develop strategies to solve single-digit arithmetic (e.g., Barrouillet, Mignon, & Thevenot, 2008; Geary, 2013; Siegler, 1996). At first, children use counting to solve small additions and subtractions and these strategies are sometimes executed with additional support, such as fingers. Through repeated use of counting, children develop problem-answer associations or arithmetic facts, which are stored in their long-term memory (Siegler & Shrager, 1984). Developing strong problem-answer associations is useful because solving arithmetic by directly retrieving facts is more efficient than using (time-consuming) counting strategies (e.g., Bailey, Littlefield, & Geary, 2012). There are large individual differences in the acquisition and use of fact retrieval (Dowker, 2005) and these might be explained by variations in children's numerical processing skills.

Vanbinst, Ghesquière, and De Smedt (2012) have recently addressed this issue in a cross-sectional study in third graders. They showed for the first time that numerical processing was associated with individual differences in strategy use in single-digit arithmetic up to 20: Children who were more proficient in discriminating Arabic digits, but not dot arrays, retrieved more arithmetic facts from their memory and executed fact retrieval faster and more accurately. The data by Vanbinst et al. (2012) are, however, cross-sectional, and they do not allow us to infer whether numerical processing skills precede children's (growth in) single-digit arithmetic. We therefore aimed to investigate with a longitudinal design, whether numerical processing predicts first graders' future single-digit arithmetic. We specifically focused on the start of formal schooling, because we wanted to examine this association at the early stages of mathematics instruction and arithmetic fact development.

It should be noted that arithmetic fact development is also predicted by various non-numerical cognitive skills, such as verbal working memory, visuo-spatial short-term memory and processing speed (e.g., Bull, Espy, & Wiebe, 2008; Holmes, Adams, & Hamilton, 2008). Specifically, a recent meta-analysis by Friso-van den Bos, van der Ven, Kroesbergen, and van Luit (2013) highlighted that especially verbal working memory and visuo-spatial short-term memory were strongly associated with arithmetic. Verbal working memory supports the acquisition of arithmetic facts in early childhood (e.g., Barrouillet & Lépine, 2005; Lefevre et al., 2013) and is crucial for keeping track of different steps during arithmetic problem solving (Imbo & Vandierendonck, 2007a). Visuo-spatial short-term memory is particularly important during the early stages of learning arithmetic when children rely on (visuo-spatial) strategies such as finger counting (e.g., De Smedt et al., 2009; Rasmussen & Bisanz, 2005). It is also important to point out that individual differences in both verbal working memory (Xenidou-Dervou, van Lieshout, & van der Schoot, 2013) and visuo-spatial short-term memory (Caviola, Mammarella, Cornoldi, & Lucangeli, 2012) have been related to measures of numerical processing in kindergarten. On the other hand, children's processing speed, which includes children's capacity to recall information from long-term memory, is associated with individual differences in arithmetic fact retrieval (e.g., Hecht, Torgesen, Wagner, & Rashotte, 2001; Koponen, Aunola, Ahonen, & Nurmi, 2007). Processing speed might also play an important role in numerical processing tasks, as these tasks are often analyzed in terms of reaction times. Because these non-numerical cognitive skills correlate with both arithmetic fact retrieval and numerical processing, these factors should be considered when investigating the association between numerical processing and arithmetic fact retrieval to determine whether numerical

processing skills make independent contributions to later individual differences in single-digit arithmetic.

Against this background, the present longitudinal study investigated whether numerical processing skills at the onset of formal schooling uniquely predict future individual differences in single-digit arithmetic. The study comprised children who started primary school and who did not yet receive formal mathematics education. At the beginning of first grade, symbolic and nonsymbolic numerical magnitude comparison tasks were administered. We also included digit naming as an additional measure of symbolic processing. We subsequently evaluated their arithmetic skills and strategy use in the middle of first grade and at the start of second grade.

To carefully examine the unique predictive power of numerical processing on future individual differences in single-digit arithmetic we included a set of additional measures. First, participants completed a general curriculum-based standardized mathematics achievement test at primary school entrance, which evaluates children's mathematical abilities at the start of formal mathematics instruction. We also assessed three non-numerical cognitive predictors, i.e. verbal working memory, visuo-spatial short-term memory and processing speed. Non-numerical tasks were used in order to prevent task performance to be influenced by numerical processing. To rule out potential effects of intellectual ability, a measure of intelligence was also administered.

1. Method

1.1. Participants

Participants were typically developing children from three elementary schools in Flanders (Belgium). At the start of first grade (September 2011) the initial sample consisted of 88 participants. In the middle of first grade (February 2012) arithmetic data were available for 84 participants of the initial sample. At the start of second grade (September 2012) arithmetic data were available for 67 participants. We only included those participants whose arithmetic data were available at two subsequent time points, because we wanted to evaluate improvements in arithmetic over time. School absence, due to illness, at one or more time points or changing schools, led to missing data. This final sample ($n = 67$) comprised 38 girls and 29 boys (M_{age} at primary school entrance: 6 years and 2 months; $SD = 3$ months). The participants came predominantly from middle- to upper middle-class families and their native language was Dutch. They had no history of developmental disorders and none had repeated a grade. Written informed parental consent was obtained for all participants.

1.2. Materials

Materials consisted of standardized tests, paper-and-pencil-tasks and computer tasks designed with the E-prime 1.0 software (Schneider, Eschmann, & Zuccolotto, 2002).

1.3. Numerical processing

1.3.1. Digit naming

In the digit naming task, each of the numbers 1 to 9 was successively presented twice on the computer screen. The child was asked to name each digit. Reaction time (RT) was registered by a voice key, after which the answer was entered on the keyboard by the experimenter. There were two practice trials to make the child familiar with task administration.

1.3.2. Numerical magnitude comparison

Children's numerical magnitude processing skills were measured by means of symbolic and nonsymbolic numerical magnitude comparison tasks, consisting of Arabic digits and dot arrays, respectively. In these tasks children had to compare two simultaneously presented numerical

magnitudes, one displayed on the left side of the computer screen, and one displayed on the right. Children had to indicate the larger of those two numerical magnitudes by pressing a key on the side of the larger one. They were instructed to perform both accurately and fast. Stimuli comprised all combinations of numerosities 1 to 9, yielding 72 trials for each task. In half of the trials the largest numerosity appeared on the left and in half of the trials the largest numerosity was presented on the right. Nonsymbolic stimuli were generated with the MATLAB script provided by Piazza, Izard, Pinel, Le Bihan, and Dehaene (2004) and were controlled for non-numerical parameters, such as dot size, total occupied area, and density, to minimize that decisions were dependent on non-numerical cues or perceptual features. A trial started with a 200 ms fixation in the center of the screen. After 1000 ms, stimuli appeared and remained visible until the child responded, except for the nonsymbolic numerical magnitude comparison task, where the stimuli disappeared after 840 ms, to avoid counting the number of dots. Each trial was initiated by the experimenter with a control key. RT and answers were registered by the computer. To familiarize children with the key assignments, three practice trials were included per task.

1.4. Single-digit arithmetic

Children's arithmetic skills were assessed with a single-digit addition and subtraction task. Stimuli were selected from the so-called standard set of single-digit arithmetic problems (Lefevre, Sadesky, & Bisanz, 1996), which excludes tie problems (e.g., $3 + 3$) and problems containing 0 or 1 as operand or answer. Only small problems in which the solution remained below or equal to 10 were selected because children in the middle of first grade only received instruction in these problems. This resulted in a set of 14 problems per operation. Children were asked to perform both accurately and fast. Responses were verbal. A voice key registered the child's RT, after which the experimenter recorded the answer. Children could use whatever strategy they wanted to. On a trial-by-trial basis, the experimenter asked the children to verbally report the strategy they used. Similar to other studies in arithmetic (e.g., Imbo & Vandierendonck, 2007b; Torbeyns, Verschaffel, & Ghesquière, 2004), strategies were classified into *retrieval* (i.e., if the child immediately knew the answer and there was no evidence of overt calculations), *procedure* (i.e., if the child indicated that (s)he used counting or almost-doubling to arrive at the solution), or *other* (i.e., if the child did not know how (s)he solved the problem). This classification method is a valid and reliable way of assessing children's single-digit arithmetic strategy use (Siegler & Stern, 1998). Two practice trials were presented to familiarize children with task administration.

1.5. Additional measures

1.5.1. Preschool mathematical abilities

Children's preschool mathematical abilities were assessed using a standardized general mathematics achievement test from the Flemish Student Monitoring System (Dudal, 2000). This untimed achievement test involves the number domain 1 to 10 and was developed to be assessed at the start of formal mathematics instruction. The test consists of 50 items, covering various aspects of mathematics: spatial concepts, counting, understanding of the meaning of ordinal numbers (e.g., first, second), magnitude comparison (e.g., understanding of the concepts less, more, and equal), word problem solving, measurement and mathematical language (e.g., understanding of concepts such as shortest, deeper, and higher). For each child, a standardized score ($M = 100$, $SD = 15$) was calculated.

1.5.2. Verbal working memory

A listening span task from the working memory test battery for children (Pickering & Gathercole, 2001), adapted to Dutch (e.g., De Smedt et al., 2009 for more elaborated task details), was used. In this non-numerical task, children had to judge the correctness of a series of

recorded sentences. They also had to memorize the last word in every sentence, and to recall those words in the presented order at the end of each trial.

1.5.3. Visuo-spatial short-term memory

The Corsi block recall task from the working memory test battery for children (Pickering & Gathercole, 2001) was used to assess children's visuo-spatial short-term memory (e.g., De Smedt et al., 2009 for more elaborated task details). For each trial, the experimenter tapped out a sequence, at a rate of one block per second, on a board with nine blocks. The child had to reproduce the sequence in the correct order.

1.5.4. Processing speed

Processing speed was evaluated with a rapid automatic naming task (van den Bos, Zijlstra, & Van den Broeck, 2003), which involved the naming of colors. The presented test card consisted of 50 stimuli, with each stimulus (black, blue, red, yellow, and green) appearing 10 times. Prior to testing, the child was required to name the stimuli in the last column to determine whether the child was familiar with all the presented stimuli. The time to complete the card was recorded for each task.

1.5.5. Intellectual ability

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

1.6. Procedure

All participants completed the administered tasks individually in a quiet room at their own school, except for Raven's matrices and the general mathematics achievement test, which were group-based. At primary school entrance, all participants completed a standardized general mathematics achievement test. Digit naming, numerical magnitude comparison, verbal working memory, visuo-spatial short-term memory and processing speed skills were assessed at the start of first grade (September 2011). Intellectual ability was assessed in December 2011. Single-digit arithmetic was evaluated in the middle of first grade (February 2012) and at the start of second grade (September 2012).

2. Results

2.1. Descriptive analyses

2.1.1. Cognitive skills at primary school entrance

Table 1 presents the descriptive statistics of measures collected at the start of first grade. This table illustrates that the data were well distributed without ceiling or floor effects.

2.1.2. Single-digit arithmetic

Children's performance on the single-digit addition and subtraction tasks was evaluated in terms of accuracy, RT and the frequency of fact retrieval. Trials with incorrect responses or incorrect voice-key registrations (<2% of all trials) were not included in the RT and strategy use data. Trials deviating more than 3SDs from the average participant's RT and trials with a RT below 500 ms (<0.5% of all trials) were excluded.

Fig. 1 presents the mean accuracy and RT for solving single-digit arithmetic per operation per time. A 2×2 repeated measures ANOVA with operation (addition vs. subtraction) and time (grade 1 vs. grade 2) as within-subject factors was conducted on accuracy and RT. A main effect of operation was observed: Additions were solved more accurately ($F(1, 66) = 18.19$, $p < .01$, $\eta_p^2 = .22$) and faster ($F(1, 66) = 9.99$, $p < .01$, $\eta_p^2 = .13$) than subtractions. There was a main effect of time, indicating that both accuracy ($F(1, 66) = 60.19$, $p < .01$, $\eta_p^2 = .48$) and RT ($F(1, 66) = 13.34$, $p < .01$, $\eta_p^2 = .17$) improved over developmental time. With regard to accuracy, operation interacted with time

Table 1
Descriptive statistics of the measures collected at the start of first grade ($n = 67$).

	M	SD	Range	Maximum possible
Digit naming				
Accuracy (% correct)	92.24	11.12	55 – 100	100
RT (ms)	998.23	282.57	571.35 – 2029.92	
Symbolic numerical magnitude comparison				
Accuracy (% correct)	88.50	7.74	58 – 97	100
RT (ms)	1458.93	349.19	875.49 – 2423.46	
Nonsymbolic numerical magnitude comparison				
Accuracy (% correct)	82.34	8.54	58 – 99	100
RT (ms)	874.194	196.90	605.44 – 1811.32	
Preschool mathematical abilities	104.19	10.91	65.50 – 121.30	
Verbal working memory	3.31	1.45	0 – 6	15
Visuo-spatial short-term memory	7.09	2.11	3 – 12	27
Processing speed (s)	68.79	17.28	40 – 118	
Intellectual ability	105	14.05	80 – 141	

Note. RT = Reaction time.

($F(1, 66) = 17.51, p < .01, \eta_p^2 = .21$). Post-hoc t -tests revealed operation differences in first grade ($t(66) = 5.02, p < .01, d = 0.68$), but not in second grade ($t(66) = 0.21, p = .83, d = 0.03$). The RT analyses showed no Operation $\times$ Time interaction ($F(1, 66) = 0.01, p = .92, \eta_p^2 = .00$).

Children's single-digit arithmetic strategy use was examined by determining the frequency of fact retrieval (Table 2) and procedural strategies on the correctly solved items. The frequency of trials belonging to the "other" category was very low (<0.5%) and these trials were further excluded. Frequencies of procedural strategy use were not reported, given that the frequencies of fact retrieval and procedural strategy use are about the inverse of each other as the "other" category was nearly zero.

A repeated measures ANOVA on the mean frequencies of fact retrieval was calculated with operation (addition vs. subtraction) and time (grade 1 vs. grade 2) as within-subject factors. This analysis revealed a main effect of operation ($F(1, 66) = 4.14, p = .046, \eta_p^2 = .06$), suggesting that fact retrieval was more frequently used during addition than during subtraction. There was a main effect of time ($F(1, 66) = 98.70, p < .01, \eta_p^2 = .60$): children showed an increasing reliance on fact retrieval over developmental time. There was a significant Operation $\times$ Time interaction ($F(1, 66) = 14.27, p < .01, \eta_p^2 = .18$). Post-hoc t -tests revealed that the operation differences were significant in grade 1 ($t(66) = 4.03, p < .01, d = 0.40$), but not in grade 2 ($t(66) = -0.43, p = .67, d = -0.06$).

Fig. 1. Mean error rate (% incorrectly solved problems) and RT on single-digit arithmetic per operation per time. Bars depict error rates on the left y-axis and lines represent RT on the right y-axis. Error bars represent 1SE of the mean.

Table 2
Mean frequencies of the use of fact retrieval per operation per time ($n = 67$).

	Addition	Subtraction
Grade 1	5.58 (3.17)	4.33 (3.18)
Grade 2	8.57 (2.60)	8.72 (2.83)

Note. Maximum possible = 14. Standard deviations are presented between parentheses.

2.2. Correlational analyses

First, Pearson correlation coefficients were calculated to examine associations between cognitive skills, intellectual ability and preschool mathematical abilities (Table 3). Pearson correlational analyses were also used to explore predictive associations between cognitive skills and individual differences in single-digit arithmetic in the middle of first grade as well as the start of second grade (Table 4). Because subtraction and addition performance was strongly correlated (all $r_s > .45$) and because the same pattern of predictive associations was observed for both operations, we averaged data across operations.

Additionally, predictive associations between cognitive skills and children's development in single-digit arithmetic were considered (Table 5). Arithmetic development was indexed by subtracting performance in grade 1 from performance in grade 2. These difference scores showed that children became more accurate ($M = 10.00\%$; $SD = 10.56$; $t(66) = 7.76, p < .01$), faster ($M = -1233.15$ ms; $SD = 2763.84$; $t(66) = -3.65, p < .01$) and used more fact retrieval ($M = 3.69$; $SD = 3.04$; $t(66) = 9.94, p < .01$), over developmental time.

2.3. Regression analyses

Regression analyses were conducted to determine the unique contribution of numerical processing measures to later individual differences and developmental changes in single-digit arithmetic. First, we verified whether each significant predictive association between a numerical processing measure and single-digit arithmetic remained when children's intellectual ability and preschool mathematical abilities were controlled for. Second, we tested the unique contribution of all the numerical processing measures that significantly predicted single-digit arithmetic, by entering them all simultaneously in a regression model.

2.3.1. Single-digit arithmetic in grade 1

Symbolic comparison accuracy uniquely predicted children's arithmetic accuracy ($\beta = .24, t = 2.03, p < .05$, unique $R^2 = .06$) and RT ($\beta = -.44, t = -3.76, p < .01$, unique $R^2 = .18$). None of the other numerical processing measures emerged as unique predictors.

Digit naming RT, symbolic comparison accuracy and symbolic comparison RT were unique predictors of children's fact retrieval use. When these three measures were simultaneously entered into the regression model, only symbolic comparison RT remained significant ($\beta = -.32, t = -2.45, p < .05$, unique $R^2 = .07$).

2.3.2. Single-digit arithmetic in grade 2

Nonsymbolic comparison accuracy was the only numerical processing measure that uniquely predicted children's arithmetic accuracy. Both digit naming RT and symbolic comparison RT significantly contributed to children's arithmetic RT. When exploring the relative contribution of these two measures, only symbolic comparison RT remained significant ($\beta = .28, t = 1.99, p = .05$, unique $R^2 = .06$).

Digit naming RT, symbolic comparison RT, nonsymbolic comparison accuracy and nonsymbolic comparison RT were all significant predictors of fact retrieval. When entering these measures simultaneously into a model, only nonsymbolic comparison accuracy ($\beta = -.32, t = -2.45, p < .01$, unique $R^2 = .07$) remained significant. It is important to point out that the three RT measures were highly correlated (see Table 3). To explore the effect of these intercorrelations, a series of additional

Table 3Associations between the measures collected at the start of first grade ($n = 67$).

	1	2	3	4	5	6	7	8	9	10
1 Digit naming ACC										
2 Digit naming RT	-.60**									
3 Symbolic comparison ACC	.34**	-.38**								
4 Symbolic comparison RT	-.28*	.50**	.08							
5 Nonsymbolic comparison ACC	.26*	-.18	.13	-.16						
6 Nonsymbolic comparison RT	-.09	.34**	.04	.67**	-.03					
7 Verbal working memory	.20	-.18	.12	-.08	-.08	.02				
8 Visuo-spatial short-term memory	-.07	-.22	.20	-.27*	.03	-.13	.09			
9 Processing speed	-.35**	.52**	-.12	.36**	.01	.05	-.15	-.20		
10 Intellectual ability	.10	.02	.25	.02	.21	.02	.22	.17	.21	
11 Preschool math	.36**	-.33**	.13	-.32**	.22	-.12	.36**	.27*	-.13	.37**

Note. ACC = Accuracy. RT = Reaction time. * $p < .05$. ** $p < .01$.

regression analyses were conducted. First, digit naming RT, nonsymbolic comparison accuracy and nonsymbolic comparison RT were entered simultaneously in a model, revealing that only the two nonsymbolic measures remained significant. In the second model, symbolic comparison RT, nonsymbolic comparison accuracy and nonsymbolic comparison RT were entered. Nonsymbolic comparison accuracy remained a significant predictor of arithmetic fact retrieval, symbolic comparison RT became a marginally significant predictor, whereas the contribution of nonsymbolic RT was not significant. Third, a regression model was run with digit naming RT, symbolic comparison RT and nonsymbolic comparison accuracy. In this model only symbolic comparison RT and nonsymbolic comparison accuracy remained significant. Based on this additional series of regression analyses, we estimated a new model in which we considered nonsymbolic comparison accuracy ($\beta = .30$, $t = 2.64$, $p < .05$, unique $R^2 = .08$) and symbolic comparison RT ($\beta = .42$, $t = 3.65$, $p < .01$, unique $R^2 = .16$) as predictors of children's use of arithmetic fact retrieval. Both these measures emerged as significant predictors.

2.3.3. Development in single-digit arithmetic from grade 1 to grade 2

The numerical processing measures did not predict children's development in arithmetic accuracy. Symbolic comparison accuracy significantly predicted children's development in arithmetic RT ($\beta = .44$, $t = 3.64$, $p < .01$, unique $R^2 = .31$) and increasing reliance on arithmetic fact retrieval ($\beta = -.27$, $t = -2.18$, $p < .05$, unique $R^2 = .13$).

2.3.4. The influence of non-numerical cognitive skills

We performed an additional series of regression analyses in order to evaluate whether the numerical processing measures that emerged as unique predictors of future individual differences in single-digit arithmetic in the sections described above, remained after verbal working

memory, visuo-spatial short-term memory and processing speed were taken into account. Table 6 gives an overview of the numerical processing predictors with unique contributions to future individual and developmental differences in single-digit arithmetic after taking into account the above mentioned additional measures.

The analyses indicate that numerical processing measures that uniquely predicted children's future single-digit arithmetic continued to be significant predictors after verbal working memory, visuo-spatial short-term memory and general processing speed were additionally controlled for, except for children's arithmetic accuracy in the middle of first grade that was no longer predicted by symbolic comparison accuracy. Symbolic comparison accuracy became a marginally significant predictor of children's arithmetic fact development.

3. Discussion

While recent longitudinal evidence suggests that numerical processing skills predict children's future general mathematics achievement (e.g., De Smedt et al., 2013, for a review) it remains largely unexplored whether this predictive association also applies to more specific mathematical skills, such as arithmetic fact development. Importantly, it remains to be verified whether such predictive associations remain when other factors that have been shown to contribute to individual differences in arithmetical competence are controlled for.

The present data provide longitudinal evidence that children's numerical processing skills at the start of formal schooling are predictively related to their future single-digit arithmetic and reliance on arithmetic fact retrieval. These predictive associations are independent of children's intellectual ability, preschool mathematical abilities, verbal working memory, visuo-spatial short-term memory and processing speed.

Our findings are in agreement with previous longitudinal studies that observed predictive associations between symbolic numerical

Table 4Predictive associations between cognitive skills and single-digit arithmetic per time ($n = 67$).

	Middle grade 1 Single-digit arithmetic			Start grade 2 Single-digit arithmetic		
	ACC	RT	Fact retrieval ^a	ACC	RT	Fact retrieval ^a
Digit naming ACC	.33**	-.14	.17	.11	.21	.19
Digit naming RT	-.30*	.24*	-.39**	-.26*	.33**	-.31*
Symbolic comparison ACC	.33**	-.46**	.36**	.10	.00	.03
Symbolic comparison RT	-.21	.09	-.32**	-.23	.39**	-.42**
Nonsymbolic comparison ACC	.27*	-.10	.05	.39**	.15	.36**
Nonsymbolic comparison RT	-.03	.13	-.22	-.04	.25*	-.37**
Verbal working memory	.11	.10	-.02	.05	.02	-.06
Visuo-spatial short-term memory	.15	-.08	.21	.11	.03	.10
Processing speed	-.17	.09	-.15	-.09	.31*	-.14

Note. ACC = Accuracy. RT = Reaction time. ^a Frequency of fact retrieval use. * $p < .05$. ** $p < .01$.**Table 5**Predictive associations between cognitive skills and children's single-digit arithmetic development ($n = 67$).

	Grade 1 to grade 2 development in single-digit arithmetic		
	ACC	RT	Fact retrieval
Digit naming ACC	-.30*	-.02	-.02
Digit naming RT	.18	.02	.13
Symbolic comparison ACC	-.30*	.44**	-.32**
Symbolic comparison RT	.10	.21	-.02
Nonsymbolic comparison ACC	-.09	-.02	.23
Nonsymbolic comparison RT	.01	.06	-.07
Verbal working memory	-.10	-.08	-.03
Visuo-spatial short-term memory	-.10	.06	-.13
Processing speed	.13	.15	.03

Note. ACC = Accuracy. RT = Reaction time. The variables accuracy, reaction time and fact retrieval represent change in single-digit arithmetic between grade 1 to grade 2. * $p < .05$. ** $p < .01$.

Table 6

Overview of numerical processing predictors with unique contributions to single-digit arithmetic after taking into account intellectual ability, preschool mathematical abilities, verbal working memory, visuo-spatial short-term memory and processing speed.

Single-digit arithmetic	Numerical processing predictor	β	t	unique R^2
Middle grade 1				
ACC	Symbolic comparison ACC	.21	1.69°	.04
RT	Symbolic comparison ACC	-.45	-3.76**	.18
Fact retrieval	Symbolic comparison RT	-.32	-2.53*	.08
Start grade 2				
ACC	Nonsymbolic comparison ACC	.36	2.85**	.12
RT	Symbolic comparison RT	.30	2.27*	.07
Fact retrieval	Nonsymbolic comparison ACC	.27	2.35*	.07
	Symbolic comparison RT	-.41	-3.28**	.13
Development				
RT	Symbolic comparison ACC	.48	3.89**	.20
Fact retrieval	Symbolic comparison ACC	-.26	-1.96°	.10

Note. ACC = Accuracy. RT = Reaction time. Frequency of fact retrieval use. * $p < .05$. ** $p < .01$. ° $p = .10$. °° $p = .06$.

processing skills and future general mathematics performance (e.g., Bartelet et al., 2014; De Smedt et al., 2009; Sasanguie et al., 2012, 2013). Our data go beyond the previous ones by showing that children's digit naming as well as symbolic numerical magnitude processing skills are predictively associated with their development of single-digit arithmetic. When evaluating the unique contribution of both these symbolic processing measures, symbolic numerical magnitude comparison performance turned out to be the best cognitive predictor of future individual differences and developmental changes in children's single-digit arithmetic. This suggests that children who are at primary school entrance more proficient at processing symbolic magnitudes will perform better on single-digit arithmetic in the early years of primary school.

Consistent with Desoete et al. (2010), we found that nonsymbolic numerical magnitude comparison performance was predictively related to arithmetic proficiency in second grade, although such predictive association was not observed for the middle of first grade. It is important to emphasize that there are inconsistent results on the association between nonsymbolic numerical magnitude processing and mathematical competence (e.g., De Smedt et al., 2013). This inconsistency might be explained by methodological issues in the design of stimuli in nonsymbolic numerical magnitude comparison tasks. Gebuis and Reynvoet (2012a) showed that the decision on the more numerous dot array is influenced by numerical as well as visual characteristics of the dot array, even if one tries to control for these visual parameters, which might facilitate or interfere with the decision process. Gilmore et al. (2013) further explored this issue and showed that only performance on incongruent trials, i.e. those dot arrays in which the more numerous array consists of visually smaller dots and a smaller area, of the nonsymbolic numerical magnitude comparison task correlated with mathematical competence. As a consequence, on these trials children have to inhibit visual characteristics but selectively attend to the numerical characteristics of the dot arrays. These trials reflect inhibitory skills rather than numerical processing and this was subsequently confirmed when showing that the association between incongruent trials and mathematical competence disappeared when inhibition skills were additionally accounted for. This finding is in agreement with studies that demonstrated strong associations between inhibition skills and mathematical competence (e.g., Blair & Razza, 2007; Scüts, Devine, Soltesz, Nobes, & Gabriel, 2013). Individual differences in inhibition skills might explain why children's nonsymbolic numerical magnitude comparison performance emerged as a predictor of second grade arithmetic performance. It might be that at this point in development, when children have developed a set of problem-answer associations, successful arithmetic performance also depends on inhibiting the incorrect answer from long-term memory (e.g., Geary, Hoard, & Bailey, 2012). Further research is however necessary to investigate this possibility.

The current study also revealed that early numerical processing skills continued to predict future individual differences and developmental changes in single-digit arithmetic above verbal working memory, visuospatial short-term memory and processing speed. Surprisingly, children's verbal working memory and visuospatial short-term memory were not longitudinally associated with single-digit arithmetic. These findings are in line with some published studies (e.g., Andersson, 2008; Rasmussen & Bisanz, 2005), but they differ from others (e.g., Andersson & Lyxell, 2007; Jarvis & Gathercole, 2003; Lefevre et al., 2013; Krajewski & Schneider, 2009). The absence of associations between arithmetic and the included non-numerical cognitive skills might be due to our restricted focus on single-digit arithmetic in the number domain up to 10. This is supported by the meta-analysis of Friso-van den Bos et al. (2013) who concluded that children rely on verbal working memory and visuo-spatial short-term memory to a larger extent when solving more complex mathematical tasks (e.g. general standardized achievement tests), than when performing on tests measuring one specific type of mathematical skill. Our data are in line with this as the measures of verbal working memory and visual-spatial short-term memory were significantly associated with children's preschool mathematical abilities.

The longitudinal design of the study and the additional control for preschool mathematical abilities provide strong evidence for the idea that proficient numerical processing skills precede children's development of single-digit arithmetic in the early years of primary school. It is important to point out that this conclusion only applies to children's development of basic arithmetic in the number domain up to 10 and further research is needed to extend this research to other components of arithmetic, i.e., multi-digit arithmetic, calculation principles, place value, estimation, applying arithmetic for solving word problems (Dowker, 2008). We also would like to emphasize that the current sample remains rather restricted, given that the children came from middle- to upper middle-class neighborhoods. Future studies should therefore include more varied samples in terms of social background. Such studies should also consider children with mathematical difficulties. Finally, in view of the large differences between countries in the age at which formal mathematics education starts, it might be fruitful to investigate the association between numerical processing and arithmetic in cross-cultural studies with children from different educational systems.

The current data do not allow us to establish bidirectional connections between numerical processing and single-digit arithmetic development. This calls for an extensive longitudinal data collection, which should preferably start before children receive formal mathematics instruction, and in which numerical processing tasks as well as different measures of arithmetic should be administered at different measurement occasions. This will allow us to discover whether the associations between numerical processing and children's arithmetic competence change over developmental time (e.g., Cowan et al., 2011; Dowker, 2005). Future research should also investigate whether other tasks that have been used to evaluate numerical processing, such as number line estimation (e.g., Booth & Siegler, 2006) or counting (LeFevre et al., 2006) are unique predictors of single-digit arithmetic development. Such research should also consider other non-numerical cognitive skills than those investigated in the current study. For example, it might be interesting to examine how visual processing (e.g., Gebuis & Reynvoet, 2012b) as well as inhibition (e.g., Gilmore et al., 2013) might explain the association between nonsymbolic numerical magnitude comparison performance and arithmetic.

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