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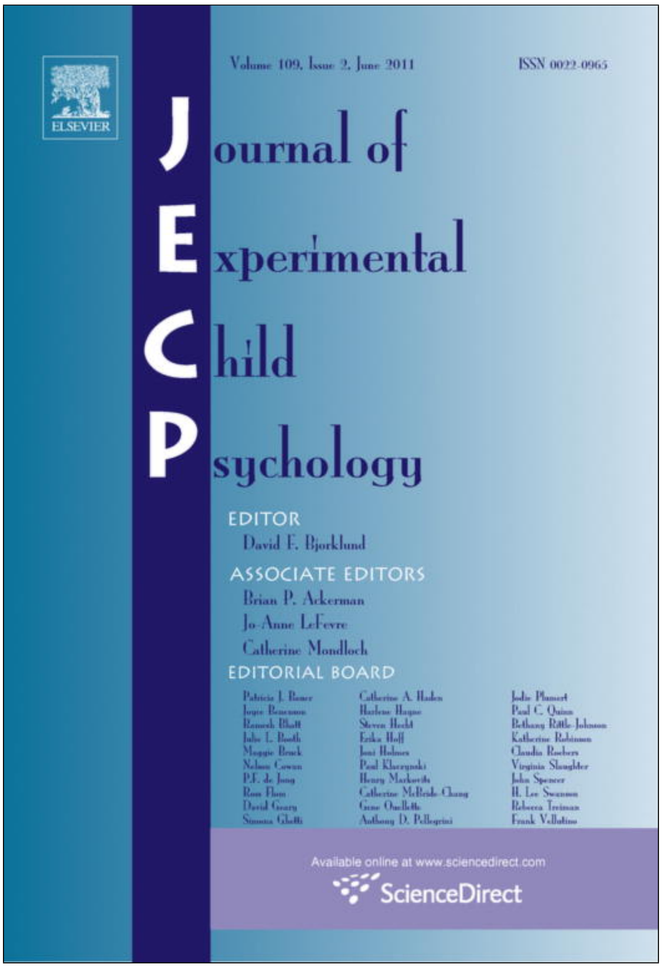

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Children's representation of symbolic and nonsymbolic magnitude examined with the priming paradigm

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ABSTRACT

How people process and represent magnitude has often been studied using number comparison tasks. From the results of these tasks, a comparison distance effect (CDE) is generated, showing that it is easier to discriminate two numbers that are numerically further apart (e.g., 2 and 8) compared with numerically closer numbers (e.g., 6 and 8). However, it has been suggested that the CDE reflects decisional processes rather than magnitude representation. In this study, therefore, we investigated the development of symbolic and nonsymbolic number processes in kindergartners and first, second, and sixth graders using the priming paradigm. This task has been shown to measure magnitude and not decisional processes. Our findings revealed that a priming distance effect (PDE) is already present in kindergartners and that it remains stable across development. This suggests that formal schooling does not affect magnitude representation. No differences were found between the symbolic and nonsymbolic PDE, indicating that both notations are processed with comparable precision. Finally, a poorer performance on a standardized mathematics test seemed to be associated with a smaller PDE for both notations, possibly suggesting that children with lower mathematics scores have a less precise coding of magnitude. This supports the defective number module hypothesis, which assumes an impairment of number sense.

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Introduction

Complex numerical processing is a product of education, but nonsymbolic processes such as the discrimination between nonsymbolic magnitudes (e.g., arrays of dots) is suggested to be innate and can already be observed in infants as well as in animals (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri, 2009; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). This basic understanding of quantity is thought to lie at the basis of the development of symbolic mathematics (Barth, La Mont, Lipton, & Spelke, 2005). The development of mental representations of magnitude has been frequently studied using the magnitude comparison task, where participants are presented with two numbers and need to judge which number is numerically larger. When the distance between the numbers decreases, participants respond more slowly and make more errors (Moyer & Landauer, 1967). This behavioral effect is referred to as the comparison distance effect (CDE) and is suggested to originate from partially overlapping neural representations of nearby numbers (Moyer & Landauer, 1967; Restle, 1970). This means that a specific number (e.g., 4) will activate not only its corresponding representation but also the representations of numbers that are numerically close (e.g., 3 and 5), following a Gaussian distribution. Recently, however, several studies have demonstrated that the CDE is not the result of a representational overlap but instead is due to decisional processes (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Holloway & Ansari, 2008; Van Opstal, Gevers, De Moor, & Verguts, 2008). A CDE has been shown to be common to both numerical and nonnumerical comparisons, suggesting that the CDE reflects a domain-general comparison mechanism (Holloway & Ansari, 2008) or a general sensorimotor transformation (Cohen Kadosh et al., 2008). In addition, it has been argued that the CDE can be dissociated from a more direct behavioral measure of magnitude representation, namely the priming distance effect (PDE) (van Opstal et al., 2008). In the priming task, two numbers are presented consecutively: the prime and the target. The distance between the prime and the target is directly related to the behavioral response, the PDE, meaning faster responses for numerically close prime–target pairs than for pairs that are numerically more distant. Unlike the CDE, this PDE cannot be explained on the basis of response processing; representational overlap is necessary to allow the prime to elicit activation of the target representation to shorten reaction times (Van Opstal et al., 2008). Therefore, the priming paradigm seems to be a better tool for investigating magnitude representation of numbers.

Studies with adults have shown that a PDE is observed not only when both the prime and target are symbolic numbers but also when they are presented as nonsymbolic magnitudes such as dot collections (e.g., Herrera & Macizo, 2008; Koechlin, Naccache, Block, & Dehaene, 1999; Roggeman, Verguts, & Fias, 2007). It is assumed that symbolic representations emerge after repeatedly linking a quantity with the number symbol to which it relates, resulting in the ability to automatically access symbolic representation (Dehaene, 1992). Using the numerical Stroop paradigm, it has been shown that an association between Arabic digits and their meaning gradually develops in children and is fully automated at around 7 or 8 years of age (Gebuis, Cohen Kadosh, de Haan, & Henik, 2009; Gebuis, Herfs, Kenemans, de Haan, & van der Smagt, 2009; Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). Some authors suggest a deficit in this automatic access to number magnitude from symbols in children with dyscalculia (Holloway & Ansari, 2009; Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007; Rubinsten & Henik, 2005), whereas others propose an impairment of the nonsymbolic representations (e.g., Butterworth, 2005; Halberda, Mazzocco, & Feigenson, 2008; Mundy & Gilmore, 2009; Mussolin, Mejias, & Noël, 2010). In the latter case, mathematical competence has been suggested to relate to differences in the internal magnitude representation (Butterworth, 2005). However, evidence for this hypothesis is based on the CDE and has not yet been investigated with the PDE. Therefore, it is not clear to what extent these individual differences in mathematics relate to differences in magnitude processes, decisional processes, or both.

To date, the majority of research using the PDE as a measure for number representation has focused on adults. Only recently did Reynvoet, De Smedt, and Van den Bussche (2009) conduct a cross-sectional study to examine the PDE in first graders (mean age = 6.7 years). They demonstrated that the PDE for symbolic numbers (i.e., digits) was already present at this age but also, more important, that the size of this effect was similar to that found in older children and adults, suggesting a rather

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stable internal magnitude representation from 6 years onward. This is contradictory to the results of studies using the number comparison task, where a decrease in the size of the CDE with increasing age has been shown (Duncan & McFarland, 1980; Holloway & Ansari, 2008; Sekuler & Mierkiewicz, 1977). The presence of a stable internal magnitude representation for the priming task but not the comparison task again underlines the notion that both tasks might not measure similar neural processes. Therefore, it can be questioned whether the development of the magnitude representation starts at an earlier age than currently thought. The study of Reynvoet and colleagues (2009) included children from first grade onward who already had received a considerable amount of formal education with symbols, possibly resulting in a stable magnitude representation for symbolic stimuli at the time of testing.

In the current study, we investigated the development of symbolic and nonsymbolic number processes using the priming task, which has been shown to measure number and not decisional processes (Van Opstal et al., 2008). Although the responses on the target do indeed contain a decision process (comparison with 5), the PDE itself is not moderated by these decision processes because these are similar in all prime–target conditions. We tested children from four different age groups—kindergartners and first, second, and sixth graders—and collected data of the participants' scores on a standardized mathematics test to assess their general mathematical ability. Inclusion of the kindergartners allowed us to investigate the development of number representations before a considerable amount of formal education had been received. The direct comparison between the nonsymbolic and symbolic notations reveals whether the effects are specific to notation. Changes in the representation of symbolic numbers, but not nonsymbolic numbers, are expected given that automatic access to symbols is supposed to develop gradually with increasing age and schooling, whereas a nonsymbolic magnitude representation is already present at infancy (Xu & Spelke, 2000; Xu et al., 2005). In addition to the development of number representations, we compared the PDE and CDE versus children's mathematical performance. Similar to previous magnitude priming studies (Cohen Kadosh et al., 2008; Herrera & Macizo, 2008; Koechlin et al., 1999; Reynvoet et al., 2009), we asked participants to judge the numerical size of both the prime and target (larger or smaller than 5). In this manner, we could get a measure of not only the PDE (responses to the target as a function of the prime–target distance) but also the CDE (responses to the prime as a function of the distance to the comparison number 5).

Method

Participants

Participants were recruited from an elementary school in Belgium. We tested 31 kindergartners, 33 first graders, 38 second graders, and 40 sixth graders, of which 24 kindergartners (mean age = 5.6 - years, 12 boys and 12 girls), 28 first graders (mean age = 6.7 years, 11 boys and 17 girls), 29 second graders (mean age = 7.6 years, 12 boys and 17 girls), and 35 sixth graders (mean age = 11.6 years, 11 boys and 24 girls) were included in the analyses. Of the 26 children who were excluded from the analyses, for 1 child we could not obtain data on the standardized achievement test, 9 children were diagnosed with a learning or developmental disability, 9 children had less than half of the trials correct, and 7 children responded too slowly or made too many errors (3 standard deviations above average).

Stimuli and procedure

Number knowledge test

Before starting the priming experiment, all kindergartners and first graders needed to conduct a simple task to measure their knowledge of the Arabic digits 1 to 9 and the numerosity they represent. First, children were asked to read the numbers 1 to 9 (which were printed on the left side of the sheet) aloud to ensure that they recognized the digits. Next they needed to connect the numbers to pictures on the right side of the sheet representing different numbers of clowns. Each participant was given 1

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point for each correct association. Children who scored less than 9 of 9 were excluded from the analyses of the priming experiment.

Symbolic and nonsymbolic priming task

Stimuli were presented at the center of the screen in white on a black background using E-Prime 1.0 (Psychology Software Tools). The symbolic stimuli consisted of Arabic digits ranging from 1 to 9 (Arial font, measuring 2–3 mm in width and 5 mm in height), whereas the nonsymbolic stimuli consisted of arrays of 1 to 9 dots. The visual properties of the stimuli (e.g., total area occupied and item size) were controlled using the MatLab program as described in Dehaene, Izard, and Piazza (2005). The dots of a single stimulus were displayed in a circle with a radius of 45 mm. Children sat at approximately 50 cm from the screen.

For both the symbolic and nonsymbolic versions of the task, prime–target pairs were created by combining primes ranging from 1 to 9 (except 5) and targets 1, 4, 6, and 9, resulting in 32 prime–target pairs. In this manner, 16 trials consisted of a prime and target that were either smaller or larger than 5 (hereafter referred to as response congruent trials), whereas the other 16 trials consisted of a prime and target of which one was smaller than 5 and the other was larger than 5 (hereafter referred to as response incongruent trials). The 16 trials that comprised a congruent prime–target pair were also presented in reverse order because we did not want the participants to notice that the numerosities 1, 4, 6, and 9 were always presented as the second numerosity. This resulted in a total of 48 trials. The 32 *response congruent trials* consisted of 8 pairs each of distance 0 (1–1, 4–4, 6–6, and 9–9, each presented twice), distance 1 (2–1, 3–4, 7–6, 8–9, 1–2, 4–3, 6–7, and 9–8), distance 2 (3–1, 2–4, 8–6, 7–9, 1–3, 4–2, 6–8, and 9–7), and distance 3 (4–1, 1–4, 9–6, and 6–9, each presented twice). The *response incongruent trials* consisted of prime–target pairs of distance 2 (6–4 and 4–6), distance 3 (7–4 and 3–6), distance 4 (8–4 and 2–6), distance 5 (6–1, 9–4, 1–6, and 4–9), distance 6 (7–1 and 3–9), distance 7 (8–1 and 2–9), and distance 8 (9–1 and 1–9).

The procedure was similar to that of Reynvoet and colleagues (2009). Children were tested in a quiet room accompanied by two experimenters. Kindergartners were tested in groups of 4 children. First, second, and sixth graders were tested in groups of 7 to 10 children. Participants were instructed to classify both prime and target as smaller or larger than the standard 5 by pressing the corresponding button. Children were asked to respond as quickly as possible but to avoid making errors. The instructions of the priming task were explained in detail by one of the experimenters. Before each experiment started, participants performed five practice trials selected at random from all possible trials presented in the experiment. During the practice trials, feedback on accuracy was provided. All children first conducted the symbolic priming task and afterward conducted the nonsymbolic priming task.[1] To prevent fatigue, a short break between the two conditions was provided. A trial consisted of the following: a fixation cross (600 ms), the prime (until a response), a blank screen (200 ms), the target stimulus (until a response), and a blank screen (2000 ms). In total, the experiment took approximately 25 min. All participants received a small reward after finishing the experiment.

Mathematical achievement

The mathematical skills of kindergartners were assessed by the test "Numerical Understanding" (Verachtert & Dudal, 2004). The scores on the test administered at the start of the last year of kindergarten were used. This test consists of 40 items covering magnitude comparison (e.g., understanding of the concepts less, more, and equal), place value and space (e.g., understanding of concepts such as middle and last), understanding of the meaning of the ordinal numbers up to 10 (e.g., first, second), mathematics language (e.g., understanding of concepts such as shortest, deep, and higher), and counting. Cronbach's α for this test is .93 (Verachtert, 2003). Mathematical skills of the elementary school children were assessed using a curriculum-based standardized achievement test for mathematics from the Flemish Student Monitoring System (Deloof, 2005; Dudal, 2000, 2001). The scores on the test administered in the middle of the school year were used. The reliability indexes of Kuder–Richardson

[1] These priming experiments were part of a larger study of number processing in children where all children needed to conduct four basic number tasks—a comparison task, a same–different task, a priming task, and a number line estimation task—with symbolic and nonsymbolic stimuli. The symbolic and nonsymbolic versions of each task were presented sequentially.

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(KR 20) for the test are .90, .89, and .88 for first, second, and sixth grade, respectively. This test has 60 items covering number knowledge, understanding of operations, (simple) mathematics, word problem solving, measurement, and geometry. The mean raw scores of the norm groups were 26.34 (SD = 9.36), 46.57 (SD = 7.98), 44.10 (SD = 9.36), and 37.83 (SD = 9.60) for kindergartners (n = 3746), first graders (n = 1215), second graders (n = 1335), and sixth graders (n = 1436), respectively. The mean raw scores of the kindergartners, first graders, second graders, and sixth graders who were included in our analyses were 35.00 (SD = 5.28), 51.25 (SD = 5.95), 48.59 (SD = 6.79), and 41.74 (SD = 8.21), respectively.

Data analyses

Priming distance effect

We examined the PDE by analyzing the performance on the targets as a function of the distance between the prime and the target (for a similar approach, see Reynvoet et al., 2009). In line with previous studies, the PDE is computed on the basis of the response congruent trials only (see also Koechlin et al., 1999; Reynvoet et al., 2009). Response incongruent trials lead to a response interference effect that masks the numerical distance effect (e.g., Reynvoet, Caessens, & Brysbaert, 2002). In addition, all trials on which the prime and target were identical (16.7%) were excluded because it has been shown that the repeated presentation of a number can lead to the bypassing of the semantic comparison stage (Dehaene, 1996; Reynvoet et al., 2009). Furthermore, only children who responded to the prime and target correctly in at least half of the trials were included in our analyses. Finally, trials on which an incorrect response was given on the prime stimulus were also excluded prior to the analyses.

Mean error rates on the targets and median reaction times (RTs) of the correct responses were calculated for all participants. The raw scores of the children were transformed to Z-scores per grade and were used as a measure of mathematical ability.

To investigate the possible differences in stimulus notation and mathematical ability, mean error rates for the responses to the targets and the median RTs for correct responses to the targets were submitted separately to a repeated measures analysis with stimulus notation (symbolic or nonsymbolic) and prime–target distance (1, 2, or 3) as within-participant factors, grade (kindergartners, first graders, second graders, or sixth graders) as a between-participants factor, and mathematical ability as a covariate.

To control for individual differences in RTs and to capture the PDE in one measure, we also computed a normalized measure of the PDE for each individual. Similar to previous research (e.g., Holloway & Ansari, 2009; Maloney, Risko, Preston, Ansari, & Fugelsang, 2010; Reynvoet et al., 2009), this was done by subtracting the average RT on trials with a prime–target distance of 1 from the average RT on trials with a prime–target distance of 3. The RT difference was then divided by the average RT on trials with a numerical prime–target distance of 1. For the error rates, the average error rate on trials with a prime–target distance of 1 was subtracted from the average error rate on trials with a prime–target distance of 3. A repeated measures analysis was conducted on this computed measure of the PDE with stimulus notation (symbolic or nonsymbolic) as a within-participant factor, grade (kindergartners, first graders, second graders, or sixth graders) as a between-participants factor, and mathematical ability as a covariate.

Comparison distance effect

It has been shown that the CDE decreases with increasing age (e.g., Duncan & McFarland, 1980; Holloway & Ansari, 2009). We wanted to verify this by conducting additional analyses on the prime stimuli as a function of the distance between the prime and the standard 5. Only the performance on the prime stimuli was analyzed because performance on prime stimuli is not confounded by prime–target distance and response congruency (see also Reynvoet et al., 2009). Median RTs of the correct responses and mean error rates on the combination of primes 1 and 2 (i.e., primes smaller than and far from the standard), primes 3 and 4 (i.e., primes smaller than and close to the standard), primes 6 and 7 (i.e., primes larger than and close to the standard), and primes 8 and 9 (i.e., primes larger than and far from the standard) were calculated for each participant and were entered separately in a

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repeated measures analyses with stimulus notation (symbolic or nonsymbolic), size (smaller or larger than the standard 5), and prime–standard distance (close to or far from the standard 5) as within-participant factors, grade (kindergartners, first graders, second graders, or sixth graders) as a between-participants factor, and mathematical ability as a covariate. In the Results section below, not all statistics are reported because we wanted to focus on the CDE and the interaction with grade.

We also computed a normalized measure of the CDE by subtracting the average RT on trials with a prime–standard distance of 3 and 4 (i.e., the average of the median RTs on the prime combinations 1 and 2 and combinations 8 and 9) from the average RT on trials with a prime standard distance of 1 and 2 (i.e., the average of the median RTs on the prime combinations 3 and 4 and combinations 6 and 7). The RT difference was then divided by the RT on trials with a prime–standard distance of 3 and 4. For the error rates, the average error rate on trials with a prime–standard distance of 3 and 4 was subtracted from the average error rate on trials with a prime–standard distance of 1 and 2. A repeated measures analysis was conducted on this computed measure of the CDE with stimulus notation (symbolic or nonsymbolic) as a within-participant factor, grade (kindergartners, first graders, second graders, or sixth graders) as a between-participants factor, and mathematical ability as a covariate.

Results

Number knowledge task

All children were able to read the digits aloud correctly. However, 2 kindergartners were removed from the analyses because they did not succeed in 9 of 9 attempts to match a group of clowns to the corresponding Arabic number. The remaining 22 kindergartners and all first graders did not make any mistakes.

Priming task

Priming distance effect

Error rates. The repeated measures analysis showed a main effect of prime–target distance, $F(2, 108) = 17.099$, $p < .0001$, $\eta_p^2 = .240$; participants made more errors when the distance between the prime and the target increased (see Table 1). No main effect of stimulus notation was observed ($F < 1$), indicating a similar performance for the symbolic and nonsymbolic conditions. Grade did not influence performance either given that no main effect for grade was shown, $F(3, 109) = 1.616$, $p = .190$. In addition, mathematical ability did not affect performance ($F < 1$), implicating that participants made a comparable number of mistakes irrespective of their mathematical ability. A significant interaction between distance and grade was found, $F(6, 216) = 2.370$, $p = .031$, $\eta_p^2 = .062$. Pairwise

Table 1
Mean percentage error rates and reaction times (with normalized standard deviations) on the targets as a function of prime–target distance.

	Prime–target distance					
	Symbolic condition			Nonsymbolic condition		
	1	2	3	1	2	3
Error rates (%)						
Kindergartners	.04 (.02)	.10 (.02)	.08 (.02)	.03 (.02)	.10 (.02)	.10 (.02)
First graders	.06 (.01)	.03 (.01)	.09 (.01)	.04 (.01)	.05 (.01)	.06 (.01)
Second graders	.04 (.01)	.02 (.01)	.09 (.01)	.03 (.01)	.07 (.01)	.10 (.02)
Sixth graders	.03 (.01)	.07 (.02)	.08 (.01)	.02 (.01)	.05 (.01)	.04 (.01)
Reaction times (ms)						
Kindergartners	1236.02 (44.39)	1375.05 (31.47)	1351.48 (42.43)	1147.18 (22.90)	1191.27 (33.18)	1232.14 (28.75)
First graders	1101.29 (34.35)	1130.66 (34.87)	1228.34 (25.11)	975.25 (17.59)	1024.63 (24.75)	1016.34 (20.79)
Second graders	894.36 (20.20)	944.71 (30.90)	936.12 (23.76)	879.95 (13.11)	896.83 (13.66)	973.10 (11.93)
Sixth graders	578.86 (7.63)	590.40 (12.68)	634.86 (11.26)	611.43 (9.74)	612.94 (11.77)	644.30 (9.14)

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comparisons showed that the differences were most pronounced at distance 2; kindergartners made significantly more errors than first graders ($p = .008$) and second graders ($p = .015$). No other significant differences were found (all *ps* > .055). All other two-way interactions were not significant (all *Fs* < 1.252 and all *ps* > .295), as were the three-way interactions (all *Fs* < 1.306 and all *ps* > .275).

The repeated measures analysis with the computed measures of the PDE revealed no main effect of stimulus notation and grade (both *Fs* < 1) (see Table 2). The main effect of mathematical ability ($F < 1$) was not significant, as were the two-way interactions (all *Fs* < 2.138 and $p > .147$).

Reaction times. The repeated measures analysis revealed a main effect of prime–target distance, $F(2, 108) = 18.892$, $p < .0001$, $\eta_p^2 = .259$, indicating that RTs were larger when the distance between the prime and the target increased (see Table 1). A main effect of grade was observed, $F(3, 109) = 60.928$, $p < .0001$, $\eta_p^2 = .626$, showing that RTs decreased with increasing grade (see Table 1). There was also a main effect of stimulus notation, $F(1, 109) = 16.257$, $p < .0001$, $\eta_p^2 = .130$, indicating that children were slower in the symbolic condition than in the nonsymbolic condition. No main effect of mathematical ability was observed ($F < 1$). A significant two-way interaction between stimulus notation and grade was found, $F(3, 109) = 7.041$, $p < .0001$, $\eta_p^2 = .162$. Pairwise comparisons showed that kindergartners ($p < .010$) and first graders ($p < .0001$) were slower in the symbolic condition than in the nonsymbolic condition, whereas no difference between the notation conditions was present for the second and sixth graders. A significant two-way interaction was found between prime–target distance and mathematical ability, $F(2, 108) = 3.985$, $p < .050$, $\eta_p^2 = .069$, indicating that

Table 2
Normalized mean priming distance effects per grade.

	Symbolic condition	Nonsymbolic condition
Error rates (%)		
Kindergartners	.05 (.13)	.07 (.16)
First graders	.03 (.11)	.05 (.12)
Second graders	.05 (.13)	.07 (.14)
Sixth graders	.05 (.09)	.02 (.09)
Response times (ms)		
Kindergartners	.13 (.24)	.09 (.17)
First graders	.14 (.21)	.07 (.19)
Second graders	.06 (.17)	.11 (.14)
Sixth graders	.11 (.15)	.07 (.15)

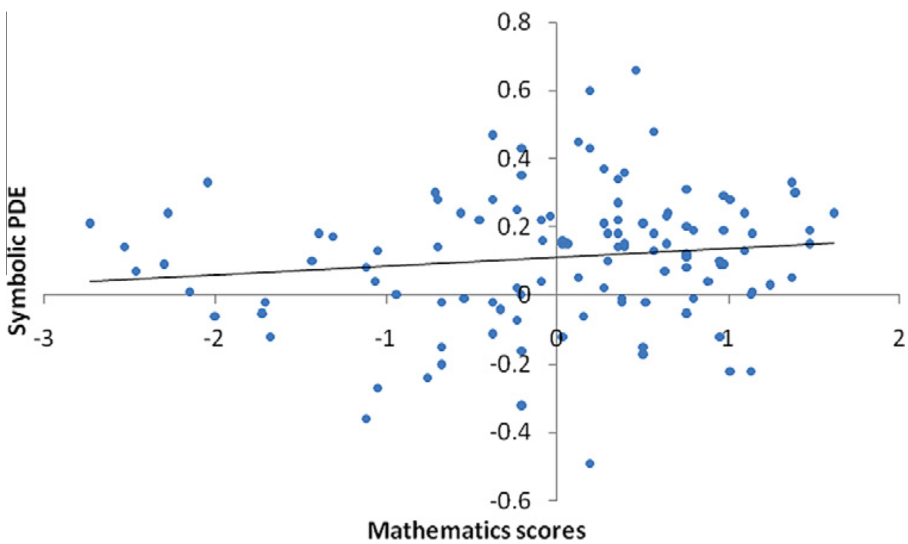

Fig. 1. Scatter plot showing the relation between the symbolic priming distance effect and the mathematics scores.

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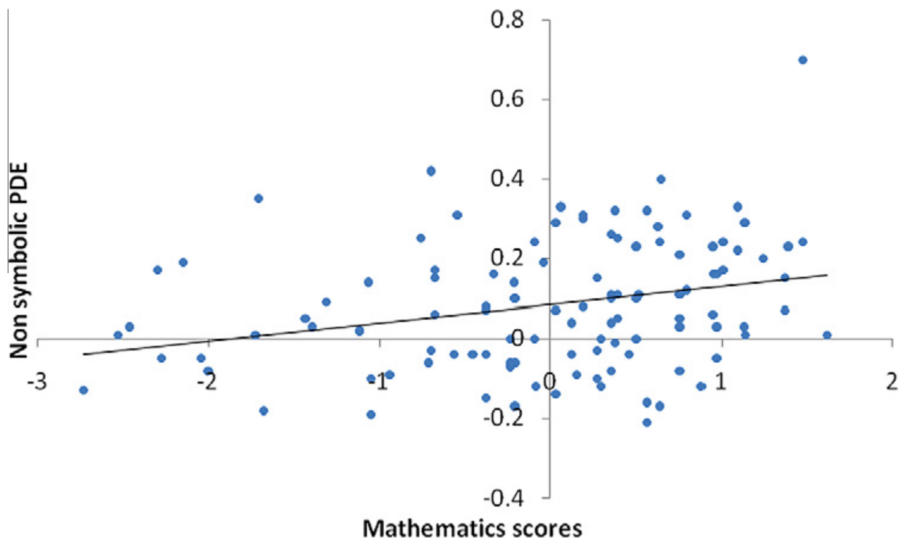

Fig. 2. Scatter plot showing the relation between the nonsymbolic priming distance effect and the mathematics scores.

mathematical ability influenced the distance effect (see below for a more specific analysis). All other two-way interactions (all *F*s < 1) and three-way interactions (all *F*s < 1.410 and all *p*s > .212) were not significant.

The repeated measures analysis with the normalized PDE yielded no main effect of stimulus notation, $F(1, 109) = 1.166$, $p = .283$, meaning that the PDE was similar for both the symbolic and nonsymbolic notations (see Table 2). Moreover, no main effect of grade was present ($F < 1$), suggesting that the PDE did not change with increasing age. In contrast, a main effect of mathematical ability was present, $F(1, 109) = 9.612$, $p < .010$, $\eta_p^2 = .081$, showing that a larger PDE is associated with a higher score on a standardized mathematics test (see Figs. 1 and 2). No significant two-way interactions were found (all *F*s < 1.252 and all *p*s > .294).

Comparison distance effect

Error rates. The repeated measures analysis on the error rates showed a main effect of prime–standard distance, $F(1, 109) = 35.521$, $p < .0001$, $\eta_p^2 = .246$); participants made more errors when the distance to the standard decreased (see Table 3). Grade also affected performance given that a main effect for grade was shown, $F(3, 109) = 3.316$, $p < .050$, $\eta_p^2 = .084$), indicating that the amount of mistakes decreased with increasing grade. The two-way interaction between distance and grade was not significant ($F < 1$), probably because of the low amount of errors. The repeated measures analysis with the normalized measures of the CDE revealed no main effect of grade ($F < 1$) (Table 4; see Table 5 for the other effects).

Reaction times. The repeated measures analysis on the RTs revealed a main effect of prime–standard distance, $F(1, 109) = 156.054$, $p < .0001$, $\eta_p^2 = .589$), indicating that RTs were larger on numerically close trials than on numerically far trials (see Table 3). A main effect of grade was observed, $F(3, 109) = 55.573$, $p < .0001$, $\eta_p^2 = .605$), showing that RTs decreased with increasing grade. Moreover, a significant two-way interaction between prime–standard distance and grade was found, $F(3, 109) = 8.101$, $p < .0001$, $\eta_p^2 = .182$. Post hoc pairwise comparisons showed a significant decrease of the RTs with increasing grade on both close and far trials (all *p*s < .050). The only exception was the absence of a difference between kindergartners and first graders on close trials ($p = .801$).

The repeated measures analysis with the normalized CDE yielded a main effect of grade, $F(3, 109) = 3.870$, $p < .050$, $\eta_p^2 = .096$. Pairwise comparisons showed that first graders had a significantly greater nonsymbolic CDE than sixth graders ($p = .019$) and tended to have a greater nonsymbolic CDE than kindergartners ($p = .083$) and second graders ($p = .066$). No other significant differences in the size of the nonsymbolic CDE were found between the groups (all *p*s > .655). A similar result was found for the symbolic CDE; first graders showed a greater CDE than kindergartners

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Table 3
Mean percentage error rates and mean reaction times (with normalized standard deviations) on the primes as a function of prime value and stimulus notation.

	Primes							
	Symbolic condition				Nonsymbolic condition			
	1–2	3–4	6–7	8–9	1–2	3–4	6–7	8–9
Error rates (%)								
Kindergartners	.04 (.01)	.06 (.02)	.03 (.01)	.06 (.02)	.03 (.01)	.09 (.02)	.10 (.02)	.05 (.01)
First graders	.03 (.01)	.06 (.01)	.03 (.01)	.01 (.01)	.01 (.01)	.06 (.01)	.09 (.01)	.06 (.01)
Second graders	.04 (.01)	.03 (.01)	.04 (.01)	.03 (.01)	.02 (.01)	.12 (.02)	.08 (.02)	.05 (.01)
Sixth graders	.00 (.00)	.02 (.01)	.05 (.01)	.01 (.00)	.02 (.01)	.07 (.01)	.03 (.01)	.02 (.01)
Response times (ms)								
Kindergartners	1220.84 (28.02)	1397.41 (45.62)	1248.39 (42.64)	1193.57 (48.51)	1119.66 (30.05)	1455.14 (47.16)	1246.43(49.98)	1166.57 (40.11)
First graders	1120.77 (30.00)	1401.64 (43.20)	1300.00 (54.13)	1063.98 (26.31)	983.20 (26.38)	1292.73 (33.81)	1285.77 (49.51)	1019.82 (30.67)
Second graders	880.90 (18.07)	978.59 (18.93)	1003.38 (31.66)	835.98 (13.84)	851.02 (29.33)	1053.34 (24.51)	1010.48 (42.74)	883.38 (20.26)
Sixth graders	614.94 (8.09)	716.44 (12.37)	677.86 (7.19)	615.56 (7.91)	616.51 (10.34)	782.30 (13.47)	707.16 (9.91)	650.63 (7.51)

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Table 4
Normalized mean comparison distance effects per grade.

	Symbolic condition	Nonsymbolic condition
Error rates (%)		
Kindergartners	−.00 (.09)	.05 (.08)
First graders	.03 (.07)	.04 (.08)
Second graders	.01 (.05)	.06 (.08)
Sixth graders	.03 (.05)	.03 (.07)
Reaction times (ms)		
Kindergartners	.12 (.18)	.19 (.20)
First graders	.24 (.22)	.28 (.19)
Second graders	.16 (.15)	.19 (.21)
Sixth graders	.13 (.11)	.18 (.09)

Table 5
Results of repeated measures analyses of comparison distance effect.

Effect	Hypothesis *df*	Error *df*	Error rates			Reaction times		
			F	Significance	η_p^2	F	Significance	η_p^2
Analysis 1								
Stimulus notation	1	109	15.108	.000	.122	0.262	.610	.002
Stimulus notation * Math ability	1	109	2.688	.104	.024	0.011	.915	.000
Stimulus notation * Grade	3	109	0.53	.663	.014	2.096	.105	.055
Size	1	109	0.081	.776	.001	5.383	.022	.047
Size * Math ability	1	109	0.053	.819	.000	0.048	.826	.000
Size * Grade	3	109	0.296	.828	.008	1.036	.380	.028
Distance	1	109	35.521	.000	.246	156.054	.000	.589
Distance * Math ability	1	109	0.294	.589	.003	3.613	.060	.032
Distance * Grade	3	109	0.178	.911	.005	8.101	.000	.182
Stimulus notation * Size	1	109	1.639	.203	.015	1.441	.233	.013
Stimulus notation * Size * Math ability	1	109	0.311	.578	.003	0.097	.756	.001
Stimulus notation * Size * Grade	3	109	5.003	.003	.121	1.121	.344	.030
Stimulus notation * Distance	1	109	15.334	.000	.123	5.631	.019	.049
Stimulus notation * Distance * Math ability	1	109	1.015	.316	.009	2.379	.126	.021
Stimulus notation * Distance * Grade	3	109	2.292	.082	.059	0.551	.648	.015
Size * Distance	1	109	5.068	.026	.044	12.049	.001	.100
Size * Distance * Math ability	1	109	0.014	.906	.000	0.002	.963	.000
Size * Distance * Grade	3	109	0.241	.868	.007	2.776	.045	.071
Stimulus notation * Size * Distance	1	109	2.732	.101	.024	5.195	.025	.045
Stimulus notation * Size * Distance * Math ability	1	109	1.532	.218	.014	0.027	.870	.000
Stimulus notation * Size * Distance * Grade	3	109	2.713	.048	.069	0.771	.513	.021
Math ability	1	109	1.903	.171	.017	2.205	.140	.020
Grade	3	109	3.316	.023	.084	55.573	.000	.605
Analysis 2								
Stimulus notation	1	109	15.334	.000	.123	6.224	.014	.054
Stimulus notation * Math ability	1	109	1.015	.316	.009	2.892	.092	.026
Stimulus notation * Grade	3	109	2.292	.082	.059	0.182	.908	.005
Math ability	1	109	0.294	.589	.003	3.995	.048	.035
Grade	3	109	0.178	.911	.005	3.870	.011	.096

(p = .013) and sixth graders (p = .011) and tended to have a greater CDE than second graders (p = .062), whereas no significant differences in the size of the CDE between the latter three groups were observed (all ps > .430) (see Table 5 for the other effects).

Discussion

In the current study, we examined the magnitude representation of typically developing children using symbolic and nonsymbolic priming paradigms. We investigated the development of the PDE and

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its relation to more complex mathematical abilities. Reynvoet and colleagues (2009) showed that a symbolic PDE is already present in first graders and that their PDE is similar to the PDE of older children and adults. However, these first graders had already received a considerable amount of formal education with Arabic digits, possibly masking a developmental change of the PDE. Therefore, a first goal of our study was to see whether kindergartners, who had just acquired understanding of Arabic digits but had not yet received a considerable amount of schooling, revealed a similar PDE as older children. Our results showed that a PDE for both nonsymbolic and symbolic notations was present in kindergartners and did not change over age. Apparently, formal schooling does not affect number representation given that kindergartners already seem to have stable representations.

Our PDE data reflecting an absence of a developmental shift from kindergarten onward are consistent with the findings of Reynvoet and colleagues (2009) but contradict previous studies investigating the CDE (e.g., Duncan & McFarland, 1980; Holloway & Ansari, 2009). Here a decrease in the size of the CDE with increasing age has been shown and interpreted as an increase in precision of magnitude representations when schooling advances (Holloway & Ansari, 2009; Sekuler & Mierkiewicz, 1977). When we looked at the CDE in our study, we did not find a linear decrease of the CDE over all age groups. Only first graders seemed to have a greater CDE than the other age groups, whereas no significant differences in the size of the CDE between the other groups were found. This result could be due to differences in task difficulty. Previous studies used a comparison task in which the largest of two numbers needed to be indicated (Duncan & McFarland, 1980; Holloway & Ansari, 2008; Sekuler & Mierkiewicz, 1977), whereas in our study children needed to decide whether a number was smaller or larger than 5 (see also Reynvoet et al., 2009). The latter task is clearly easier because only one new magnitude needs to be integrated in the decision process. These differences in task difficulty might have led to the disappearance of a developmental change in the CDE (see also Reynvoet et al., 2009).

We also examined whether the PDE was specific to notation. Our results did not show significant differences between the symbolic and nonsymbolic notations of the PDE, suggesting that the number representations underlying these relatively small number magnitudes (1–9) are of comparable precision for symbolic and nonsymbolic notations. However, it should be noted that the absence of a difference between the symbolic and nonsymbolic notations could be a null result possibly caused by the small number of trials (see Cohen Kadosh & Walsh, 2009). Previous studies suggested that single-digit numbers and numbers up to 15 are represented more precisely because they are the most frequently used subset of numbers in daily life (Notebaert & Reynvoet, 2008; Verguts, Fias, & Stevens, 2005). It remains to be investigated whether a difference in children's PDE between symbolic and nonsymbolic notations would be found when larger magnitudes are used. The similar effects for the symbolic and nonsymbolic versions of the priming task seem to contrast with previous studies using the numerical Stroop paradigm. Using this paradigm, it has been suggested that children who just acquired knowledge of Arabic digits have automatic access to nonsymbolic number knowledge (Gebuis, Cohen Kadosh, et al., 2009) but not to symbolic number knowledge and that automatic access to symbolic representations develops gradually with increasing age (Gebuis, Herfs, et al., 2009; Girelli et al., 2000; Rubinsten et al., 2002). This discrepancy between our results and those obtained with the Stroop paradigm is most likely related to task differences. In our priming task, participants were asked to process both prime and target magnitudes intentionally and to decide whether they were smaller or larger than 5. Asking for this explicit response might have led to similar observations for the symbolic and nonsymbolic notations that could be different if participants needed to conduct the task under automatic conditions (Cohen Kadosh & Walsh, 2009). This requires the replication of the current study, for example, by asking participants to conduct a magnitude irrelevant task on the stimuli such as naming. In this way, we can investigate whether a different PDE would be found for the symbolic and nonsymbolic notations under conditions where semantic processing of the stimuli is not necessary to conduct the task adequately.

A second goal of our study was to examine whether mathematical ability is related to the PDE. Our results revealed that a greater symbolic PDE, but also a greater nonsymbolic PDE, was associated with relatively higher scores on a standardized mathematics test. According to the representational overlap hypothesis, this result implies that the precision of both the symbolic and nonsymbolic magnitude representations relate to mathematical abilities. Our results are not in line with the access deficit

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hypothesis, which implies that children with mathematical difficulties are impaired only in symbolic number tasks (and so have difficulty in accessing the numerical meaning from symbols), whereas they have no impairments in nonsymbolic number tasks (Rousselle & Noël, 2007). On the basis of our findings and in line with previous studies, we rather expect that there can be an impairment of number sense in children who have mathematical difficulties (Butterworth, 2005; Halberda et al., 2008). This supports the defective number module hypothesis because it implies that children with mathematical difficulties show impairments in quantity processing per se (Butterworth, 2005).

To conclude, we have shown that a PDE and a CDE are already observed from kindergarten onward for both relatively small symbolic and nonsymbolic numerosities. The PDEs of kindergartners did not differ from those of older children, indicating that the magnitude representation for small numerosities is stable. Moreover, we obtained similar priming effects for symbolic and nonsymbolic stimuli, showing that both notations are processed with equal precision. Finally, a smaller PDE seemed to be associated with lower scores on a standardized mathematics test, possibly suggesting that children with the lowest scores had less precise representations of magnitude.

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