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Numerical matching judgments in children with mathematical learning disabilities

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ABSTRACT

Both deficits in the innate magnitude representation (i.e. representation deficit hypothesis) and deficits in accessing the magnitude representation from symbols (i.e. access deficit hypotheses) have been proposed to explain mathematical learning disabilities (MLD). Evidence for these hypotheses has mainly been accumulated through the use of numerical magnitude comparison tasks. It has been argued that the comparison distance effect might reflect decision processes on activated magnitude representations rather than number processing per se. One way to avoid such decisional processes confounding the numerical distance effect is by using a numerical matching task, in which children have to indicate whether two dot-arrays or a dot-array and a digit are numerically the same or different. Against this background, we used a numerical matching task to examined the representation deficit and access deficit hypotheses in a group children with MLD and controls matched on age, gender and IQ. The results revealed that children with MLD were slower than controls on the mixed notation trials, whereas no difference was found for the non-symbolic trials. This might be in line with the access deficit hypothesis, showing that children with MLD have difficulties in linking a symbol with its quantity representation. However, further investigation is required to exclude the possibility that children with MLD have a deficit in integrating the information from different input notations.

1. Introduction

It is estimated that 3–8% of the elementary school children have mathematical learning disabilities (MLD) (Desoete, Roeyers, & De Clercq, 2004). Individuals with MLD experience specific problems in arithmetic and mathematics, which are not caused by general intellectual impairment or the lack of educational opportunities (American Psychiatric Association, 2000; see Butterworth, Varma, & Laurillard, 2011 for a review). Low mathematical competence has been shown to negatively impact upon important aspects of life, such as educational and employment attainment (Duncan et al., 2007; Reyna, Nelson, Han, & Dieckmann, 2009). Therefore, several studies have tried to unravel the causes of MLD in order to develop appropriate intervention strategies. Some studies proposed that deficits in domain-general cognitive capacities (e.g. working memory, visuospatial abilities) cause MLD (Geary, 2004, 2005; McLean & Hitch, 1999; Passolunghi & Siegel, 2001; Rourke & Conway, 1997). Other researchers suggested that MLD are due to a domain-specific numerical deficit (see Rubinsten & Henik, 2009 for

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a review). In this study, we focus on the two main hypotheses that have been put forward to explain MLD in terms of a domain-specific numerical deficit.

It has been demonstrated that humans have an innate non-symbolic number sense, which supports the manipulation and comparison of numerosities (Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri, 2009). When symbols are learned, these are thought to acquire their meaning through the mapping onto this pre-existing non-symbolic magnitude representation (Barth, La Mont, Lipton, & Spelke, 2005; Mundy & Gilmore, 2009). Accordingly, one hypothesis states that MLD are caused by a deficit in this innate ability to mentally represent and process numerical magnitudes (Butterworth, 2005). This *representation deficit hypothesis* is mainly supported by studies showing that children with MLD perform more poorly than controls on non-symbolic (e.g. dot-arrays) (Mazzocco, Feigenson, & Halberda, 2011; Piazza, 2010; Price, Holloway, Raesaenen, Vesterinen, & Ansari, 2007) or both symbolic (e.g. digits) and non-symbolic (e.g. dot-arrays) (Landerl, Fussenegger, Moll, & Willburger, 2009; Mussolin, De Volder, et al., 2010; Mussolin, Mejias, & Noël, 2010) numerical magnitude comparison tasks. In these tasks, participants need to judge which of two magnitudes (e.g. digits or dot-arrays) represents the larger number. Typically, a numerical distance or ratio effect emerges which indicates faster and more accurate responses when the numerical distance or ratio is larger. These effects are assumed to originate from the mental representation of magnitude. A particular magnitude does not only activate its corresponding representation, but also to a lesser extent the representations of numerically close magnitudes, according to a Gaussian distribution (Moyer & Landauer, 1967; Restle, 1970). It is therefore more difficult to discriminate between magnitudes that are numerically close as there is more representational overlap between them. Studies supporting the representation deficit hypothesis have shown that children with MLD had a larger comparison distance effect than controls. The children with MLD were significantly slower and/or made more errors than controls when comparing magnitudes that were close together. This suggests that children with MLD have a less precise magnitude representation compared to controls (e.g. Mussolin, De Volder, et al., 2010; Mussolin, Mejias, et al., 2010; Price et al., 2007).

By contrast, other studies have demonstrated that children with MLD do not perform more poorly during the comparison of non-symbolic stimuli, but only show impairments when comparing symbolic stimuli (De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007). This latter finding gave rise to the second hypothesis, referred to as the *access deficit hypothesis* (Rousselle & Noël, 2007). According to this hypothesis, children with MLD do not have a deficient magnitude representation. Instead, they have problems in accessing the magnitude representation from symbolic magnitudes.

One caveat, however, is that evidence for both hypotheses is mainly accumulated by means of number comparison tasks (e.g. Price et al., 2007; Rousselle & Noël, 2007). It has been recently questioned to which extent these number comparison tasks index the magnitude representation. Indeed, several studies have argued that the comparison distance effect might rather be explained by more general decision processes on activated representations (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Holloway & Ansari, 2008; Van Opstal, Gevers, De Moor, & Verguts, 2008; Van Opstal & Verguts, 2011). For example, Holloway and Ansari (2008) reported a developmental decrease in the distance effect for both numerical (e.g. digits) and non-numerical (e.g. brightness) comparisons, suggesting that the comparison distance effect might reflect a general decisional mechanism. More evidence was provided by a study from Van Opstal et al. (2008), in which it was shown that the CDE can be explained by response competition (indicating the left or right magnitude as 'larger'), which decreases with increasing distance and is common for numerical and non-numerical comparisons. These authors suggested that representational overlap is not required for the CDE to emerge, see (Van Opstal et al., 2008) for a more detailed description.

One way to avoid such confounds due to decisional processes is by using a numerical matching task (Cohen Kadosh et al., 2008; Van Opstal & Verguts, 2011). In this task, participants have to judge whether two simultaneously presented magnitudes are numerically the same or different. Typically, also here a numerical distance effect is observed: matching magnitudes is more difficult when they are close to each other; for example, indicating that 5 and 7 dots are numerically the same or different is more difficult than deciding whether 5 and 9 dots are numerically the same or different. In contrast to the comparison task, the distance effect in a numerical matching task has shown to reflect the underlying mental representation of magnitude, without being confounded by decisional processes (Cohen Kadosh et al., 2008; Van Opstal & Verguts, 2011). For example, Van Opstal and Verguts (2011) observed a numerical distance effect in the comparison task when both numbers (which have representational overlap) and letters (which have no representational overlap) had to be compared. By contrast, a distance effect in the matching task only emerged with numbers and not letters, suggesting this task directly indexes the magnitude representation (Van Opstal & Verguts, 2011). Defever, Sasanguie, Vandewaetere, and Reynvoet (2012) recently examined non-symbolic (i.e. two dot-arrays) and mixed notation (i.e. digit and dot-array) matching judgments in a group of typically developing kindergartners, first-, second- and third graders. As expected, a numerical distance effect was observed but the size of this effect was not related to individual differences in mathematics achievement. This indicates that the preciseness of the mental representation of magnitudes does not differ as a function of mathematical achievement in children. However, poor mathematics achievement was associated with slower reaction times on the matching task, particularly when a digit and a dot-array had to be matched. This suggests that the speed with which a digit can activate its magnitude representation is related to mathematics achievement, which is in line with the access deficit hypothesis (Defever et al., 2012; Rousselle & Noël, 2007).

In the current study, we aimed to further address the abovementioned hypotheses about a specific deficit to number processing in children with MLD using a numerical matching task. This allowed us to investigate the replicability of the findings on comparison tasks, in which general-decision processes could have an effect on the numerical distance effect. We

Table 1
Descriptive statistics of the sample.

	MLD group	Control group
N	25	25
Gender	7 males	7 males
Age (years)	11.49 (1.03)	10.99 (.81)
Math achievement[a]	64.72 (17.21)	116.44 (19.99)
IQ[b]	91.92 (11.09)	93.92 (9.70)

[a] Mean raw score on the Arithmetic Tempo Test.
[b] IQ-score on the Standard Progressive Matrices.

presented both non-symbolic (i.e. two dot-arrays) and mixed notation (i.e. digit and dot-array) trials to children with MLD and gender, age and IQ matched controls. If children with MLD have a deficient magnitude representation, we would expect them to perform worse than controls, irrespective of the notation format. In contrast, if children with MLD have problems with associating digits with their corresponding magnitude representation, we would expect them to perform more poorly on the mixed notation trials only.

2. Methods

2.1. Ethics statement

Written informed consent was obtained from all the parents and the study was approved by the Ethical Committee of the University of Leuven.

2.2. Participants

Participants were 33 primary school children with MLD. To be part of the MLD group, children had to have a severe and persistent delay in mathematics achievement, despite receiving intensive remedial instruction (in and/or outside school). Twenty-one children attended special needs schools for children with learning disorders. Enrollment in this type of special education is only possible after formal multidisciplinary assessment by experienced clinical or educational psychologists. In order to be eligible for this type of special education, children need to have normal intellectual ability (i.e. IQ > 85, as shown on a standardized test of intelligence). They also need to have significant impairments in mathematics and/or reading, as determined by age-appropriate standardized tests. Twelve children with MLD attended regular schools and were recruited via rehabilitation centers where they received weekly remediation for their math difficulties. Similar to the special needs schools, children can only receive remediation in a rehabilitation center after taking part in a complete diagnostic testing by a multidisciplinary team. To further validate the clinical diagnosis of MLD and to have a measure on which the performance of the MLD and control participants could be compared, we administered a standardized mathematics achievement test (Tempo test arithmetic; De Vos, 1992). These data indicated that all children with MLD scored below the 10th percentile of the population sample mean. Twelve children with MLD also scored below the 10th percentile of the population sample mean on a speeded reading test (Brus & Voeten, 1999), indicating they also had additional difficulties in reading.[1]

The control participants were recruited in one regular school. A large group of 4th, 5th and 6th graders took part in an arithmetic and IQ assessment. The control participants that matched best with the MLD children on gender, age and IQ were selected, which resulted in a sample of 33 control children. All control children scored between the 30th and 100th percentile on the standardized mathematics test and between the 20th and 99th percentile on the speeded reading test.

Eight children with MLD were excluded because they fell within the clinical range for ADHD as assessed by an ADHD questionnaire (Scholte & Van der Ploeg, 1998). This resulted in a sample of 25 children with MLD (age range = 9.25–12.83 years) and 25 matched controls (age range = 9.42–12.25 years) (see Table 1 for detailed descriptive statistics). *t*-Tests indicated that the MLD group had a significant lower mathematical ability than the control group ($t(48) = -9.181$, $p < .001$). No significant differences in age ($t(48) = 1.929$, $p = .060$) and IQ ($t < 1$) were observed between the groups.

2.3. Materials

2.3.1. Experimental tasks

Numerical matching judgment task. Stimulus presentation and recording of the data were controlled by E-prime 1.1 (Psychology Software Tools, http://www.pstnet.com). In half of the trials, participants were presented with two dot-arrays (i.e. non-symbolic trials) whereas the other half consisted of one dot array and one digit (i.e. mixed notation trials) (see Fig. 1). A vertical gray line separated the two stimuli in each trial. The non-symbolic trials consisted of two dot-arrays of gray

[1] We verified whether differences in results could be found between children with only MLD and children with MLD and reading difficulties. The analysis revealed no main effect of group ($p = .648$) nor were there any other significant interactions involving group (all $ps > .314$). Therefore, we did not consider them as two separate groups in the analyses.

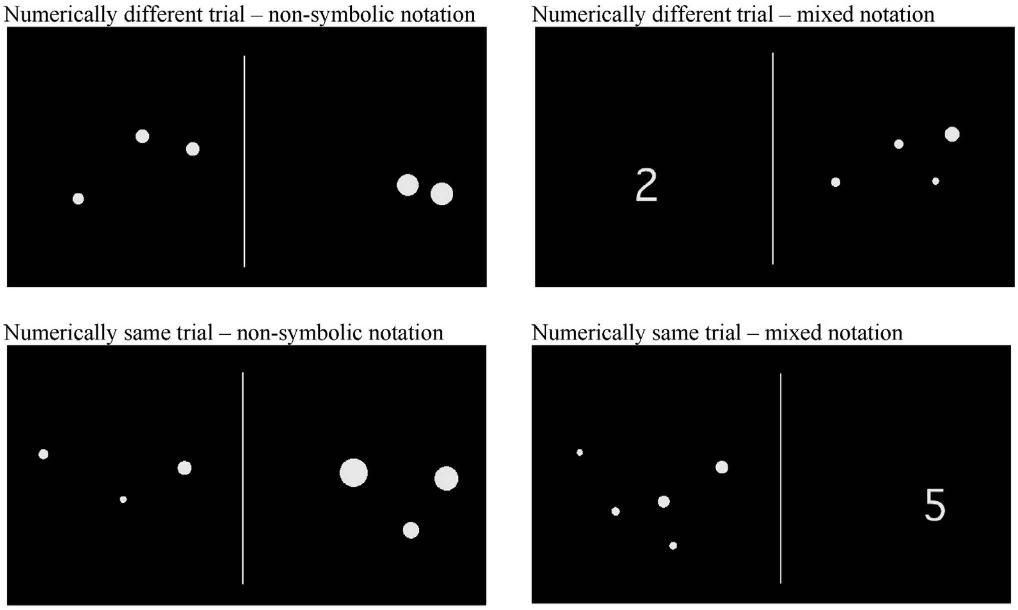

Fig. 1. Sample images of the non-symbolic and mixed notation trials.

dots on a black background, which were generated using the MatLab program developed by Gebuis and Reynvoet (2011). Three visual properties were manipulated: (1) the aggregate surface of the dots, (2) density and (3) the average diameter. Regression analyses showed that differences in the visual properties could not explain the variance in numerical distance (all R^2s < .04, all *ps* > .17). The more numerous array of the trials with two numerically different stimuli had larger visual properties in half of the trials and smaller visual properties in the other half. For the trials with two numerically same stimuli, half of the trials had the stimulus with the larger visual cues on the left side of the screen, while in the other half it was presented on the right side. Consequently, participants could not decide that two stimuli were numerically different simply because the visual stimulus properties differed.

All possible combinations of magnitudes 1–5 were used to create 24 trials with two numerically same stimuli (hereafter referred to as same trials) and 24 trials with two numerically different stimuli (hereafter referred to as different trials). The different trials consisted of 8 pairs of numerical distance 1 (1–2; 2–3; 3–4 and 4–5, each presented twice), distance 2 (1–3 and 3–5, each presented twice and 2–4 presented four times) and 8 trials with a numerical distance of 3 (i.e. 1–4; 2–5, presented 4 times each). For each trial, two non-symbolic stimuli were generated. In half of the trials the larger magnitude was presented on the left, whereas this was reversed for the other half of the trials. The mixed notation trials were identical to the non-symbolic trials, with the exception that one digit and one dot array were shown. The 48 non-symbolic and 48 mixed notation trials were presented in a fully randomized order.

Participants were asked to indicate as fast and accurately as possible whether the two stimuli represented an equal or a different number, by pressing ‘a’ (labeled with ‘=’) or ‘p’ (labeled with ‘≠’) on an AZERTY keyboard. Before the experiment started, five practice trials were given during which feedback was provided in order to make the children familiar with the task demands. Each trial was preceded by a fixation cross (i.e. 800 ms) and was presented for 1000 ms. Children could respond during the stimulus presentation or during a blank screen that followed the stimulus presentation. The next trial started after an inter-trial interval of 1000 ms. Children were seated at approximately 50 cm from the screen. In total, the experiment took about 10 min.

Processing speed task. We assessed general processing speed to exclude the possibility that observed differences in reaction time between the MLD and control group were due to a slower processing speed of children with MLD (e.g., Censabella & Noël, 2005). We used a similar task as the one described by Reigosa-Crespo and colleagues (2012). A black square was presented in the center of the screen and children were asked to press the space bar as soon as they saw the square. The interstimulus presentation time varied between 500 and 1500 ms. The test consisted of 20 trials which were preceded by five practice trials. Median reaction times were used as a measure of processing speed.

2.3.2. Standardized tests

ADHD questionnaire. Children’s teachers completed a Dutch ADHD-questionnaire to assess whether the children showed behavioral symptoms of ADHD. This questionnaire contained 18 items which assessed the presence of inattentive, hyperactive and impulsive behavior on a five-point likert scale (Scholte & Van der Ploeg, 1998). Eight children fell within the clinical range and were therefore excluded from the analyses.

One minute reading test. Word reading was assessed with the version A of the standardized Dutch one-minute reading test (Brus & Voeten, 1999). The test consists of a list of 116 unrelated words of increasing length and difficulty. Children were instructed to read aloud as many words as possible within 1 min without making errors.

Arithmetical ability. All children were tested with the Tempo test Arithmetic (De Vos, 1992). This test consists of 5 subtests: one for each type of operation (addition, subtraction, multiplication, and division) and one with mixed operations. Forty items of increasing difficulty are presented in each subtest and participants are given 1 min to solve as many problems as possible.

Intelligence test. All children completed the Standard Progressive Matrices (SPM; Raven, Court, & Raven, 1992) as a measure of intellectual ability.

2.4. Procedure

Data were collected in two sessions. In one session the 1-min-reading, arithmetical ability and intelligence tests were administered, whereas in the other session the processing speed task and the numerical matching judgment task were carried out. All participants first conducted the processing speed task and afterwards the numerical matching judgment task. For the control children, the standardized tests were administered collectively per classroom, whereas the computerized tasks were administered in groups of 5–7 children. The children were seated in such a way that they could not distract each other and the experimenter could monitor them closely. Children with MLD were tested individually.

3. Results

3.1. General processing speed

No significant difference in general processing speed was observed between the MLD (M = 321 ms, SD = 71) and control group (M = 302 ms, SD = 57) ($t(48) = -1.08$, p = .29).

3.2. Reaction times

Median RTs from correct responses on the different trials were submitted to a repeated measures analysis of variance with stimulus notation (non-symbolic or mixed notation) and distance (1, 2 or 3) as within-subject factors and group (MLD or control) as a between-subject factor. A main effect of numerical distance was observed ($F(2,47) = 15.73$, $p < .01$, $\eta_p^2 = .401$), indicating that the RTs decreased with increasing distance (see Table 2). Post hoc pairwise comparisons showed a significant difference between all levels of distance (all $ps < .050$). No main effect of group was found ($F(1,48) = 1.13$, $p = .29$). The effect of stimulus notation was significant ($F(1,48) = 5.91$, $p < .05$, $\eta_p^2 = .11$) and was embedded in a significant interaction between stimulus notation and group ($F(1,48) = 7.94$, $p < .01$, $\eta_p^2 = .14$). Post hoc pairwise comparisons showed that the groups did not significantly differ for the non-symbolic condition ($p = .84$), whereas for the mixed notation condition the MLD group was slower than the control group ($p = .05$). Moreover, no differences between the notation conditions was present for the MLD group ($p = .79$), whereas the control group was slower in the non-symbolic (i.e. 1277 ms) compared to the mixed notation condition (i.e. 1147 ms) ($p = .01$) (see Fig. 2). No other significant effects were observed (all $ps > .51$).

3.3. Error rates

Mean error rates on the different trials were submitted to a repeated measures analysis of variance with stimulus notation (non-symbolic or mixed notation) and distance (1, 2 or 3) as within-subject factors and group (MLD or control) as a between-subject factor. A main effect of numerical distance was found ($F(2,47) = 8.02$, $p < .01$, $\eta_p^2 = .25$). Post hoc pairwise comparisons showed that the number of errors decreased with increasing numerical distance ($ps < .01$), with the exception that no significant difference was found between distance 2 and 3 ($p = .65$) (see Table 2). No other significant effects were observed (all $ps > .21$).

Table 2
Mean percentage error rates (SD) and RTs (SD) as a function of stimulus notation and numerical distance for the MLD and control group.

	Non-symbolic notation			Mixed notation		
	Numerical distance					
	1	2	3	1	2	3
Error rates (%)						
MLD	21.32 (19.59)	10.76 (10.33)	10.88 (13.08)	18.24 (18.77)	10.84 (13.60)	10.76 (14.45)
Control	18.76 (18.82)	8.92 (15.02)	10.32 (14.27)	13.88 (18.73)	11.80 (16.63)	13.28 (14.76)
RTs (ms)						
MLD	1360 (375)	1283 (378)	1247 (454)	1396 (416)	1289 (308)	1234 (338)
Control	1405 (484)	1262 (356)	1163 (333)	1203 (280)	1148 (301)	1089 (222)

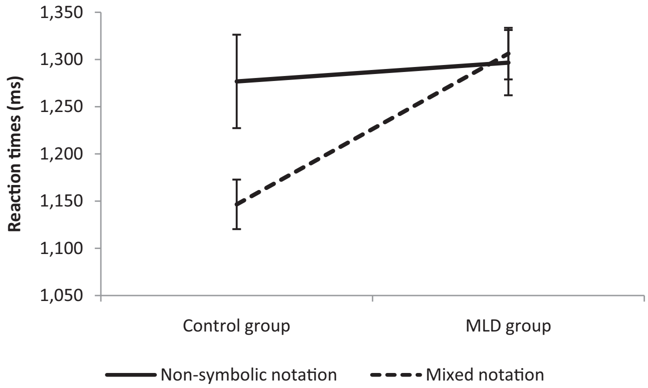

Fig. 2. The reaction times (ms) in function of stimulus notation and group. Error bars represent 95% confidence intervals (see Loftus & Masson, 1994).

4. Discussion

Two main hypotheses about a deficit specific to numerical abilities have been proposed to explain MLD. According to the representation deficit hypothesis, MLD are attributed to a deficient ability to represent numerical magnitudes (Butterworth, 2005). The access deficit hypothesis suggests that MLD are not caused by an impaired magnitude representation, but are rather due to difficulties in accessing the magnitude representation from symbols (Rousselle & Noël, 2007). Evidence in support of these hypotheses has mainly been found using number comparison tasks. However, doubt has been casted on the extent to which the comparison distance effect reflects specific number-related processes, rather than general decisional mechanisms upon activated representations (Cohen Kadosh et al., 2008; Holloway & Ansari, 2008; Van Opstal et al., 2008; Van Opstal & Verguts, 2011). In this study, we therefore used the numerical matching task to examine the representation and access deficit hypotheses further. The distance effect in a numerical matching task directly originates from the magnitude representation and not from decisional mechanisms (Van Opstal & Verguts, 2011). This allowed us to specifically examine number processing in children with MLD without decisional mechanisms confounding the distance effect. We compared the performance of children with MLD and controls matched on age, gender and IQ during non-symbolic and mixed notation matching judgments.

Our results revealed that children with MLD were slower than controls when a digit and a dot-array had to be matched, whereas no difference between the groups was observed when two dot-arrays were presented. This finding is in line with the access deficit hypothesis (De Smedt & Gilmore, 2011; Rousselle & Noël, 2007), suggesting that children with MLD mainly have problems in mapping numerical symbols onto the pre-existing non-symbolic magnitude representation. The absence of a significant interaction between numerical distance and group also supports the access deficit hypothesis rather than the representation deficit hypothesis, because it suggests that the magnitude representation is probably not impaired in children with MLD. Our observations are in line with those found in a study with typically developing children (Defever et al., 2012). In this study, non-symbolic and mixed notation numerical matching judgments were examined in a group of kindergartners, first-, second- and third graders. An interaction was found between mathematics achievement and stimulus notation. Children who performed more poorly on a standardized achievement test were slower than controls. This association was significantly stronger for the mixed notation task compared to the non-symbolic task.

Our study did not include a pure symbolic same-different task, since a same-different task with only digits or only number words could be done on the basis of the physical similarity of the stimuli (Cohen, 2009; Defever et al., 2012; García-Orza, Perea, Abu Mallouh, & Carreiras, 2012). As a consequence, it could be argued that the slower reaction times of the MLD group on the mixed notation task are not due to a deficit in accessing the numerical meaning of symbols, but rather to a deficit in integrating the information from different numerical input formats. Further research, using a pure symbolic same-different task in which a strategy based on physical similarity is avoided, is necessary to clarify whether children with MLD have an integration deficit. However, it seems likely that our findings point to a difficulty in the processing of numerical symbols since previous number line studies showed that performance on a symbolic number line task (but not a non-symbolic number line task) was (predictively) related to mathematics achievement, which cannot be explained by difficulties in integrating information from different input formats (Kolkman, Kroesbergen, & Leseman, 2013; Sasanguie, De Smedt, Defever, & Reynvoet, 2012).

In this study we only used magnitudes from 1 to 5 to examine the representation and access deficit hypothesis. Different number ranges have been used in the literature to examine number processing in participants with MLD. Researchers examining only non-symbolic number processing either use numbers above the subitizing range (4 or 5 and larger) (Mazzocco et al., 2011; Piazza et al., 2010) or use numbers both within and above the subitizing range (1–9) (Kucian, Loenneker, Martin, & Von Aster, 2011; Price et al., 2007). Researchers investigating only symbolic number processing mostly restrict the number range to the single digits 1–9 (Landerl, Bevan, & Butterworth, 2004; Mussolin, De Volder, et al., 2010;

Mussolin, Mejias, et al., 2010). When both symbolic and non-symbolic number processing skills are assessed, often numbers from 1 to 9 are included in all tasks for sake of comparability (De Smedt & Gilmore, 2011; Mussolin, De Volder, et al., 2010; Mussolin, Mejias, et al., 2010). Up to date, it is debated whether distinct representation systems exist for numbers within and above the subitizing range (Hyde, 2011). Although some studies indicate that the approximate number system operates over small and large numbers (e.g., Cantlon & Brannon, 2006; Cordes, Gelman, Gallistel, & Whalen, 2001), others suggest that small numbers are represented differently than large ones (e.g., Feigenson et al., 2004; Hyde & Spelke, 2009). Against this background, it remains an open question whether our results can be generalized to larger numerosities.

It should be noted that the children with MLD and the control children were not matched in terms of grade level. This is due to the organization of the special education system in Belgium, in which 21 of the children with MLD were enrolled in. In Belgium, there are specific segregated special education schools for children with learning disorders (e.g., ''special education of type 8''). These schools are not organized in terms of grade, instead they are organized in terms of the reading and/or math level of the child (e.g., a child could be at one level for reading, but at a different level for math). We therefore could not match our MLD and control group on grade level. However, we think that differences in grade level between our MLD and control group had little or no effect on our findings. Firstly, the matching task is a relatively simple task and only contained the magnitudes 1–5, which all children at the ages under investigation in this study (mean age = 10.99 years and 11.49 years for the control and MLD group, respectively) were familiar with. Secondly, we showed in a previous study in which a similar task with the same magnitudes was administered to a sample of typically developing children that there were no RT differences between second and third graders (Defever et al., 2012). This suggests that grade level does not affect RTs in 7- and 8-year-old children and that the current findings are probably not due to differences in grade.

Finally, we interpreted our observations in light of the common assumption that numerical symbols acquire their meaning by being mapped onto the pre-existing non-symbolic magnitude representation. However, this assumption has been questioned (Carey, 2004; Lyons, Ansari, & Beilock, 2012; Noël & Rousselle, 2011). For instance, Lyons and colleagues (2012) recently argued that the representation systems for symbolic and non-symbolic number stimuli are separate in adulthood, raising the question whether they were ever linked to begin with. Specifically, they observed that adults had more difficulties with comparing a digit and a dot-array than when two dot-arrays needed to be compared. The authors proposed that through repeated use and mastery of symbols, relations between symbols may come to overshadow those between symbols and their quantity referents. Consequentially, numerical symbols might start to primarily operate as an associative system. This leads to an extra processing cost when comparing a digit and a dot-array (Lyons et al., 2012). However, in our study, the control group was significantly faster on the mixed notation trials compared to the non-symbolic trials. This suggests that accessing the numerical meaning of a symbol did not require an additional processing cost in children. The association between a symbol and its quantity referent seems not to be overshadowed by symbol-symbol associations in children. The current data indicate that the hypothesis that the meaning of numerical symbols is gained by mapping them onto the innate magnitude representation is still plausible. A comparison of the present findings and those of Lyons and colleague (2012) suggests that symbols only start to operate as an associative system in adulthood, an issue that should be addressed in future developmental studies.

In sum, we found no significant differences between the MLD and control group for the numerical distance effect, suggesting that children with MLD have an intact magnitude representation. Our data rather supports the access deficit hypothesis (De Smedt & Gilmore, 2011; Iuculano et al., 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007), showing that children with MLD have mainly problems in accessing the intact magnitude representation from symbols. Last, our control group performed better on the mixed notation trials compared to the non-symbolic trials. This suggests that, in contrast to what has been found in adults, symbols are not estranged from their quantity representation in children.

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