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Impairment of Arabic- and Spoken-Number Processing in Children With Mathematical Learning Disability

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Abstract

The performance of 24 French-Quebec 8–9-year-old children with Mathematical Learning Disability (MLD) in Arabic and spoken number recognition, comprehension and production tasks designed to assess symbolic number processing was compared to that of 37 typically developing children (TD). Children with MLD were less successful than TD children in every symbolic numerical task, including recognition of Arabic and spoken numbers. These results thus suggested that this deficit of symbolic number recognition could compromise symbolic number comprehension and production. Children with MLD also presented with general cognitive difficulties as reading difficulties. Taken together, our results clearly showed that children with MLD presented with a symbolic numerical processing deficit that could be largely attributed to their poorer written language skills.

Keywords: Mathematical Learning Disability, Dyscalculia, number sense deficit, number sense access deficit, symbolic, recognition

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According to the American Psychiatric Association in the Diagnostic and Statistical Manual of Mental Disorders, DSM-5 (2013), specific learning disorder could take the form of deficit in the acquisition of reading, writing, arithmetic, or mathematical reasoning skills during the formal years of schooling. The learning disorder of mathematical skills in children, called developmental dyscalculia or Mathematical Learning Disability (MLD), is defined as a disorder that interferes with mathematics learning and daily life activities. MLD is manifested by difficulties in counting, enumeration, calculation, problem solving, etc. Studies on children with MLD found a prevalence from 1 to 10% (Badian, 1999; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Devine, Soltész, Nobes, Goswami, & Szűcs, 2013; Dirks, Spyer, Van Lieshout, & De Sonneville, 2008; Gross-Tsur, Manor, & Shalev, 1996; Lewis, Hitch, & Walker, 1994; Share, Moffitt, & Silva, 1988). Because mathematics is involved in many activities of daily life, people with MLD can be marginalized and their social and professional integration affected (Badian, 1999; Institut national de la santé et de la recherche médicale, 2007).

The cognitive processing of numbers has been conceptualized in various theoretical models. In the triple-code model (Dehaene, 1992, 2010) representing numerical skills in adults, numbers may be manipulated and represented mentally in three different codes: analogic, Arabic, and verbal. The analogic code (i.e., the “number sense”) is non-symbolic and represents the magnitude of numerosities over a compressible number line oriented from left to right. The Arabic and verbal codes are both symbolic and non-semantic (i.e., they do not bear number sense themselves). In the Arabic number form, numbers are manipulated in Arabic format (e.g., 3). Finally, numbers are manipulated in words (e.g., /three/) in the verbal code. Although the triple-code model was implemented to account for mature numerical processes, it provides a relevant framework for understanding the development and deficits of numerical skills in children. This model clearly describes the organization and processing of number representations and was therefore used as a theoretical framework in the present study.

Other models have been proposed to account for the development of numerical abilities in children. According to the model of number acquisition (Von Aster & Shalev, 2007), the development of cognitive number representation is achieved from infancy through the school years through four main steps. The first step consists of an inherited basic number sense based on core-system representation of magnitude (similar to the analogic code in the triple-code model). More precisely, the Exact Numerical System (ENS) sustains subitizing which is the intuitive, fast, and precise ability of perceiving and identifying small collections of objects, without counting, which is limited to 3 (Schleifer & Landerl, 2011), to 4 (Krajcsi, Szabo, & Morocz, 2013) or to 5 (Starkey & Cooper, 1995); the Approximate Numerical System (ANS) rather sustains estimation, which is the intuitive, fast, and approximate ability of perceiving and identifying large collections of more than 5 objects, without counting. Medium numerosities from 5 to 9 have a particular status because, even they depend on ANS, they are frequently met and they can be subitized and exactly identified through repetitive exposition (Clements, 1999). The second step consists of the acquisition of number words during the preschool years and in the association of a perceived number of objects with spoken number symbols (i.e., the verbal code in the triple-code model). In the third step, children learn Arabic symbols and associate them with a perceived number of objects and its corresponding number word (i.e., the Arabic code in the triple-code model). Finally, these three steps are necessary preconditions for the fourth step, which consists of developing a mature mental number line. This model provides a developmental view of number acquisition and number processing and was also used as a theoretical framework in the present study.

According to both the triple-code model (Dehaene, 1992, 2010) and the four-step developmental model of number acquisition (Von Aster & Shalev, 2007), a main numerical cognitive hypothesis can be posited to explain MLD: the “number sense” deficit. Such a deficit would lead to difficulty processing non-symbolic numbers and to impaired mental numerical representations (Davidse, de Jong, Shaul, & Bus, 2014; Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Ferreira et al., 2012; Landerl, Fussenegger, Moll, & Willburger, 2009; Mazzocco, Feigenson, & Halberda, 2011; Mejias, Mussolin, Rousselle, Grégoire, & Noël, 2012; Mussolin, Mejias, & Noël, 2010). However, some studies did not report this impairment in children with MLD (e.g., De Smedt & Gilmore, 2011; Landerl & Kölle, 2009; Rousselle & Noël, 2007). In these studies, children with MLD were efficient in comparing non-symbolic numbers (i.e., sets of dots), while their performance was not as good as that of typically developing children when they had to compare Arabic numbers. Such an impairment could hardly be interpreted as a number sense deficit, but rather suggests impairment in the connection between the Arabic and analogic codes in the triple-code model or impairment in the third step of the four-step developmental model of number acquisition. This interpretation was adopted by Noël and Rousselle (2011), who suggested that MLD is a specific deficit in the access to number sense from Arabic numbers rather than a “number sense” deficit per se (see also Lafay, St-Pierre, & Macoir, 2015 and Noël, Rousselle, & De Visscher, 2013 for a review on the numerical cognitive deficit in MLD).

The functional cognitive origin of MLD remains controversial. Some of this uncertainty stems from significant differences in the methods and tasks used to measure numerical skills in children. In previous studies, researchers usually used comparison tasks to assess numerical abilities in children with MLD and mainly found that they presented deficits in processing Arabic numbers (Davidse et al., 2014; De Smedt & Gilmore, 2011; Desoete et al., 2012; Ferreira et al., 2012; Landerl et al., 2009; Landerl & Kölle, 2009; Mejias et al., 2012; Mussolin et al., 2010; Piazza et al., 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007; Rousselle & Noël, 2007). Spoken numerals are nonetheless as important as Arabic numerals in school as well as in daily life activities and should also be considered in studies designed to address the functional origin of MLD. However, at least to our knowledge, researchers never used tasks in which children with MLD were asked to compare spoken numerals. Laski and Siegler (2007) asked kindergarteners and 6-8-year-old children with no difficulties to compare verbally presented numbers and found that their performance on magnitude comparison was correlated with their performance on number line estimation. Furthermore, in most of the reported studies, symbolic number processing was measured with comprehension tasks, while number production and number recognition tasks were used less often. When the production of symbolic numbers was investigated, researchers usually used transcoding tasks (such as analogic-to-symbolic numbers and vice versa) and found that children with MLD had difficulties in transcoding analogic numerosities (e.g., groups of dots) to symbolic spoken numbers (e.g., Mazzocco et al., 2011; Mejias et al., 2012; Olkun, Altun, & Şahin, 2015), without investigating symbolic Arabic numbers. Furthermore, Mejias et al. (2012) explored only the reverse transcoding of Arabic numbers from 8 to 64 to analogic numbers and found that 9–10-year-old children with MLD had difficulties in approximately producing a collection corresponding to an Arabic number. Surprisingly, neither study explored spoken-to-analogic numbers transcoding nor analogic-to-Arabic numbers transcoding in school-age children with MLD, so that the picture regarding the production of numbers in MLD remains incomplete. Furthermore, to the best of our knowledge, no study explored the recognition of symbolic numbers in MLD. This recognition process is, however, a prior and essential prerequisite for every numerical activity and should therefore be considered in studies designed to identify the functional locus of MLD.

Finally, the functional origin of MLD also remains controversial. According to some researchers, MLD is a pure numerical deficit that can be observed in isolation in children (Badian, 1999; Wilson & Dehaene, 2007). However, many of children with MLD also present other cognitive deficits so that other researchers have rather emphasized the role of general cognitive factors as the functional origin of MLD (Geary, 1993, 2010). Indeed, children with MLD frequently present with a verbal short term memory deficit (Rotzer et al., 2009), a visuospatial short term memory deficit (Passolunghi & Cornoldi, 2008), or even a working memory deficit (i.e., executive control) (Geary et al., 2009). Furthermore, many of them present also with dyslexia (Badian, 1999), namely 43 to 65% according to Barbaresi et al. (2005). It has been shown that children with reading difficulties could also have mathematics difficulties because of poor phonological abilities and poor verbal memory, or even poor reading comprehension (Landerl, Göbel, & Moll, 2013).

To summarize, there is still no consensus regarding the cognitive and functional origin of MLD. The originality of the present study lies in the systematic exploration, in the same group of children with MLD, of processes devoted to: the recognition of Arabic and spoken numbers, the access to number sense from Arabic and spoken numbers, the production of symbolic numbers from analogic numerosities (analogic-to-symbolic) and vice versa (symbolic-to-analogic). Moreover, the possible link between number processing and cognitive abilities was specifically examined.

The present study was designed to answer the following research questions: 1) Do children with MLD present with a deficit affecting Arabic number processing and/or spoken number processing? 2) Do children with MLD present with a deficit affecting number sense access, number production, and/or number recognition? And 3) Is the numerical deficit observed in children with MLD in relation with a more general cognitive deficit?

Methods

Participants

The focus of the present study was to investigate the numerical deficit in children who presented mathematics difficulties at school, as identified by their teacher.

Seventy-six 8- or 9-year-old third grade French-speaking children were recruited for this study. They had no history of sensory, physical, neurological, language, intellectual and/or psychiatric illness. All these children were recruited from eleven French schools in Quebec City, Canada. Of these schools, one was classified as being in a poor socioeconomic environment, nine as average, and one as being in an advantaged environment, according to the socioeconomic index published by Québec's Ministère de l'Éducation, du Loisir et du Sport (2013).

The initial research sample included 37 children with typical development and 39 children with mathematical difficulties, as identified by the child's teacher or special education teacher or speech-language pathologist. MLD is rarely diagnosed in Quebec and, therefore, we adopted an enrolment method based on the judgment by parents and teachers of mathematics abilities of children. The high proportion of children identified with mathematical difficulties was the direct result of this enrolment method, and does not represent the actual prevalence of MLD. These 39 children with mathematical difficulties met the DSM-5 (2013) criterion according to which the affected academic skills cause significant interference with academic or occupational performance. According to the DSM-5 (2013), the affected academic skills in MLD are substantially and quantifiably below those expected for the individual's chronological age, as confirmed by individually administered standardized achievement measures and clinical assessment. To insure compliance with this criterion, the Zareki-R (Dellatolas & Von Aster, 2006), a "paper-and-pencil" French battery designed to assess number processing and calculation in children aged 6 to 11 years old, was administered to all children. The selection of participants for the present study was based on recent Quebec-French normative data for third grade (Lafay, St-Pierre, & Macoir, 2016). All the 37 typical children (21 girls and 16 boys) scored above -1.5 standard deviations (*SD*) on the Zareki-R test and formed the group of typically developing (TD) children. Of the children with mathematical difficulties, 11 scored above -1.5 *SD* of the average on the total score of the Zareki-R test and were excluded from the present study. Four children were excluded because they had repeated a grade. Mathematical proficiency extends along a continuum ranging from TD to MLD. Therefore, the MLD-nominees who did not meet the DSM-5 criteria for MLD were not included in the TD group because they presented some difficulties in mathematical achievement in daily life and/or school and could not be considered as TD children, but as at risk. Finally, 24 children (20 girls and 4 boys) who scored below -1.5 *SD* of the average on the total score of the Zareki-R test formed the group of children with MLD. Teachers and parents also confirmed that MLD children had difficulties for more than six months, another diagnostic criterion of MLD according to the DSM-5 (2013).

In summary, there were 37 TD children (mean age in months = 107.3, *SD* = 3.8) and 24 children with MLD (mean age = 108.2, *SD* = 4.3). An ANOVA (analysis of variance) was performed on the mean age with the variable Group (Group: TD vs. MLD). The groups did not differ significantly in mean age ($F(1, 55) = .058$, $p = .810$, $\eta_p^2 = .001$). There were 21 girls (57%) and 16 boys (43%) in the TD group and 20 girls (83%) and 4 boys (17%) in the MLD group and the difference in gender distribution between the two groups was significant ($\chi^2(1, N = 61) = 4.666$, $\varphi = .28$, $p = .031$). The two groups (TD: 31 right-handers (84%) and 6 left-handers (16%); MLD: 19 right-handers (79%) and 5 left-handers, 21%) were equivalent in terms of handedness distribution ($\chi^2(1, N = 61) = 0.210$, $\varphi = .06$, $p = .647$). Finally, the repartition of children according to the socioeconomic environment was significantly different ($\chi^2(2, N = 61) = 10.364$, $p = .006$, Cramer's V = .412) in the two groups. The percentage of children from poor socioeconomic environment was equivalent for the two groups (TD: 6 children (16%); MLD: 2 children, 8%). The proportion of children from advantaged socioeconomic environment (TD: 23 children (62%); MLD: 7 children, 29%) and an average socioeconomic environment (TD: 8 children (22%); MLD: 15 children, 63%) however was reverse. Considering these differences, the socioeconomic status was entered as covariable in the analyses of the results on experimental tasks.

Table 1

Participants' General Cognitive Abilities: TD and MLD (mean (SD) and statistics)

			ANOVAs (Group: TD vs. MLD)		
Measure	**TD (*n* = 37)**	**MLD (*n* = 24)**	***F* (1, 59)**	***p***	η_p^2
Mathematic abilities (/163)	140.8 (9.3)	112.7 (9.8)	127.687	<.001*	.684
Dot counting (/6)	5.7 (0.5)	5.4 (0.8)	3.350	.072	.054
Backward oral counting (/4)	3.5 (0.9)	2.6 (1.2)	11.838	.001*	.167
Number dictation (/16)	15.4 (1.0)	13.4 (2.4)	20.238	<.001*	.255
Mental calculation (/44)	37.1 (4.8)	26.8 (5.9)	55.762	<.001*	.486
Number reading (/16)	15.4 (0.9)	14.2 (1.8)	12.931	.001*	.180
Number positioning on an analogic scale (/24)	17.9 (3.3)	14.2 (3.7)	17.055	<.001*	.224
Magnitude comparison on spoken numbers (/16)	14.7 (1.3)	12.2 (2.1)	34.272	<.001*	.367
Estimation of sets of dots (/5)	4.2 (0.8)	3.8 (1.2)	3.409	.070	.055
Contextual estimation of quantities (/10)	7.9 (2.5)	5.4 (2.9)	13.413	.001*	.185
Spoken problem-solving (/12)	9.1 (2.0)	5.3 (2.3)	46.907	<.001*	.443
Magnitude comparison of Arabic numbers (/10)	9.8 (0.5)	9.5 (0.7)	3.683	.060	.059
Neuropsychological abilities					
Non-verbal reasoning (/36)	28.4 (3.2)	25.6 (3.0)	10.461	.002*	.151
Processing speed (/126)	39.5 (7.4)	34.9 (5.4)	6.686	.012*	.102
Visuospatial short-term memory (/16)	7.0 (1.6)	6.3 (1.3)	3.344	.072	.054
Visuospatial working memory (/14)	6.3 (2.0)	5.4 (1.3)	3.935	.052	.063
Verbal short-term memory (/12)	9.1 (2.0)	8.2 (2.5)	2.614	.111	.042
Verbal working memory (/12)	6.9 (2.1)	5.2 (1.4)	12.776	.001*	.178
Linguistic abilities					
Reading and spelling (/90)	77.9 (6.8)	66.0 (10.0)	30.499	<.001*	.341
Word comprehension and production (/80)	53.2 (3.8)	50.7 (2.9)	7.367	.009*	.111
Reaction time (in ms)	513.9 (135.9)	634.9 (203.3)	10.022	.002*	.145

*These ability scores were significantly lower than those of TD children ($p < .05$).

A series of ANOVAs (Group: TD vs. MLD) on the total score and subtests of the Zareki-R were performed. The performance of the children with MLD was significantly poorer than that of the TD children with respect to general mathematical abilities (see Table 1).

Assessment of Neuropsychological and Linguistic Abilities

All children first underwent a general neuropsychological assessment tapping the cognitive domains sensitive to number processing. They were tested individually in a quiet room at their school. Testing took place from February to June of the school year. Each child was tested in one session lasting between 45 and 60 minutes.

The assessment battery first included measures of non-verbal reasoning with Raven's Coloured Progressive Matrices (Raven, 1977), which is known to be highly correlated to the measure of intellectual capacities (IQ) of children (Wilkes & Weigel, 1998). This test is frequently used in studies to ensure that children present good intellectual abilities. The assessment battery also included measures of processing speed with the Coding subtest of the WISC IV (Wechsler, 2003), visuospatial memory with the forward and backward span of the Corsi block test (Corsi, 1972; Isaacs & Vargha Khadem, 1989), verbal memory with the forward and backward digit repetition subtests of the Zareki-R (Dellatolas & Von Aster, 2006), spoken word comprehension and word production with the spoken word-to-picture matching and picture naming of the “Évaluation du Langage Oral” battery (Khomsi, 2001), word reading and spelling with two subtests of the “Batterie Analytique du Langage Écrit” (Cogni-science, 2010).

Since the experimental tasks were administered using a computer to record response time, a reaction time task was administered to the children. This task was presented on a computer screen with DMDX (Forster & Forster, 2003), software that allows the controlled presentation of stimuli and recording of response time. The children had to press a response button as quickly as possible each time they saw a fixation point (cross) appearing on the computer screen. In one condition, they were asked to press the red button with the index finger of their right hand and in the other condition they had to press the green button with the index finger of their left hand. In each condition, twenty fixation crosses were randomly presented with four different delays between each stimulus: 250, 500, 1000 or 1500 milliseconds. The dependent measure was the mean reaction time combined for both tasks.

The performance of the MLD group (a series of ANOVAs, Group: TD vs. MLD) was significantly lower than that of the TD group for non-verbal reasoning, processing speed, verbal working memory, word comprehension, word production, reading and spelling (see Table 1). Compared to norms of each test, no children with MLD presented with a deficit (below -1.5 *SD* of the average or below the percentile 10) in non-verbal reasoning and processing speed. Two of them presented with a deficit in verbal short-term memory and verbal working memory as well as in spoken word comprehension and word production. Finally, 12 out of the 24 children with MLD presented with a reading and spelling deficit.

A 2 (Group: TD vs. MLD) x 2 (Task: Right vs. Left reaction time) ANOVA was performed on response latencies. Children with MLD were slower than TD children ($F(1, 59) = 10.022$, $p = .002$, $\eta_p^2 = .145$). However, neither Task effect ($F(1, 59) = 0.012$, $p = .914$, $\eta_p^2 < .001$) nor interaction ($F(1, 59) = 0.044$, $p = .834$, $\eta_p^2 = .001$) were observed.

As presented in the introduction, the co-occurrence of MLD with other cognitive and linguistic disorders is very common (Badian, 1999). As a whole, this sample is representative of the population with MLD usually found in the scientific literature (Geary, 1993, 2010): children of this group present with mathematical difficulties along with cognitive and linguistic impairment. To account for the possible influence of these impairments on numerical abilities, results on cognitive and linguistic tests were entered as covariates in the analyses of the results on experimental tasks.

Experimental Tasks

TD children as well as those with MLD underwent an experimental numerical assessment designed to identify the locus of the deficit at the origin of MLD. The presentation order of the experimental tasks was randomized between children. All the stimuli were presented on a computer screen with DMDX (Forster & Forster, 2003).

Magnitude Comparison of Symbolic Numbers

The ability to access number sense from symbolic numbers was assessed with two tasks administered in the Arabic and spoken codes. They involved recognizing symbolic numbers and accessing their numerosities (in other words, number sense).

In the Arabic code, stimuli, displayed on the computer screen, consisted of two white squares (side = 10 cm) separated by a 2-cm space, containing a blue (left stimulus) and a yellow (right stimulus) Arabic number (Calibri, 22 millimeters) and children were asked to select the largest one. Magnitude comparisons were performed on 30 pairs in which numbers varied from 1 to 99. The size of numbers was controlled with regard to the ENS and the ANS, as well as to medium numerosities from 5 to 9, which had a particular position and overlapped the two previous systems. Indeed, these pairs varied along three numerical sizes: 8 small pairs from 1 to 4 were contrasted with 7 medium pairs from 5 to 9 and 15 large pairs from 10 to 99. The pairs also varied along three ratios between the numbers: 10 pairs with ratio 1/2, 10 pairs with ratio 2/3, and 10 pairs with ratio 3/4. The side of the correct response (i.e., the largest number) was counterbalanced: each pair appeared twice, once in ascending (e.g. 1-2) and once in descending (e.g. 2-1) order, for a total of 60 pairs. Pairs were presented in random order. Five practice trials were offered to allow the children to become familiar with the task.

Each trial started with the presentation of the pair, remaining on the screen until response or until 4000 milliseconds, and followed by a 500-millisecond delay. Blue and yellow stickers were respectively stuck on the left Alt key and right Alt key of the keyboard. As this task required choosing between two possible responses, one displayed on the left and one displayed on the right side, the children were asked to respond by pressing the button on the side of the correct response (i.e. the largest number). Responses and latencies were recorded by the computer, from the onset of the first number word uttered.

In the spoken code, two white squares containing blue and yellow pictures of earphones were displayed on the computer screen. The children listened to pairs of spoken numbers, separated by 1000 milliseconds, and were asked to select the largest one. They had to press the left blue button or right yellow button respectively if the largest number was the first or second number heard.

Magnitude Judgment on Analogic-Symbolic Numbers Association

Two tasks in the Arabic and spoken codes were administered to assess the ability to access number sense from symbolic numbers. More particularly, these tasks investigated the direct association between a symbolic number and the corresponding numerosity. Two numbers were presented on the computer screen and children were asked to decide if they represented the same magnitude or not. Compared to the magnitude comparison, this task is cognitively more demanding. First, the concurrent processing of two different modalities within the same trial is complex, as pointed out by Lyons, Ansari, and Beilock (2012). Second, while there is only one response choice in the magnitude comparison task, the magnitude judgement task requires a response between two possible choices (i.e. same magnitude or not), which adds to the processing load. As shown by Dietrich, Huber, and Nuerk (2015), adults are less successful in judgment than in comparison tasks with numbers, suggesting that the first one is more difficult.

In the Arabic code, a set of dots in random spatial arrangement and an Arabic number were presented on the computer screen and the children had to decide if the two numbers (set of dots and Arabic number) represented the same magnitude or not. In the spoken code, a set of dots and an earphone picture were presented on the computer screen; at the same time, the children listened to a spoken number and had to decide if the two numbers (set of dots and spoken number) represented the same magnitude or not.

Stimuli, separated by a 2-cm space, consisted of a black square (10-cm sides) containing a set of blue dots (left stimulus) and a white square containing a black Arabic number in the Arabic code (Calibri, 22 millimeters) or a yellow earphone picture in the spoken code (right stimulus).

Magnitude judgments were performed on pairs in which the numbers varied from 1 to 9. The 18 pairs varied along two numerical sizes: 9 small pairs with 1 to 4 dots, and 9 medium pairs with 5 to 9 dots. Different pairs also varied along three ratios of dots: 3 pairs with ratio 1/2, 3 pairs with ratio 2/3, and 3 pairs with ratio 3/4. The side on which the largest number was presented in pairs with two different numbers was counterbalanced: each pair appeared twice, once in ascending (e.g., 1-2) and once in descending (e.g., 2-1) order, for a total of 36 pairs. Pairs were presented in random order. Five practice trials were offered to allow the children to become familiar with the task.

Each trial started with the presentation of the pair, remaining on the screen until response or until 4000 milliseconds, and followed by a 500-millisecond delay. Green and red stickers were respectively stuck on the left Ctrl key and the right Ctrl key of the keyboard. As this task required choosing between two possible responses (“yes, the two numbers (set of dots and symbolic number) represent the same magnitude” or “no, the two numbers (set of dots and symbolic number) did not represent the same magnitude”), one displayed on the left and one displayed on the right side, the children were asked to respond by pressing the left Ctrl key button for the answer “yes” or the right Ctrl key for the answer “no”. Responses latencies were recorded by the computer from the onset of the number word uttered.

Analogic-to-Symbolic Number Transcoding

Two tasks were administered to assess symbolic number production from analogic numerosities. These tasks involved numerosity recognition as well as production of symbolic (Arabic or spoken) numbers. A set of dots in random spatial arrangement (black squares (10-cm sides) which contained a set of blue circles) was presented on the computer screen. Children were asked to estimate the numerosity represented by the dots by writing (without counting) the corresponding Arabic number on a sheet of paper (Arabic code) or by orally producing the corresponding spoken number (spoken code).

Number production was performed on sets in which the number of dots varied from 1 to 99. The 30-dot sets varied along three numerical sizes: 10 small numerosities with 1 to 4 dots (1, 1, 2, 2, 2, 3, 3, 3, 4, 4) were contrasted with 10 medium numerosities with 5 to 9 dots (5, 5, 6, 6, 7, 7, 8, 8, 9, 9) and with 10 large numerosities with 10 to 99 dots (12, 17, 26, 31, 46, 53, 64, 79, 85, and 98 for the Arabic code; 13, 18, 25, 32, 47, 51, 66, 74, 89, and 94 for the spoken code). Because of the nature of the task and the small size of dots sets, it was highly probable that children transcode small numerosities by counting dots. Therefore, in this task, we expected that children with MLD would be as successful as TD children in this condition of small numerosities.

They were presented in random order. Five practice trials were offered to allow the children to become familiar with the task.

Each trial started with the presentation of a set of dots, remaining on the screen until response or until 4000 milliseconds, and followed by a 500-millisecond delay. Because it was an estimation task and an exact response could not be expected, it was not possible to consider true or false responses in analyses. Therefore, a ratio (child's response / target number) between child's response and the target number was first calculated (for example, a ratio of 0.5 corresponded to a response of 6 for the target number 12). Second, the absolute distance (ADR) between the child's calculated ratio and the perfect ratio 1 was calculated: ADR = 1 – child's response / target number. Finally, response time was also recorded by the experimenter, who pressed a response key as soon as the child started his/her response. The response latencies were recorded from the onset of the number word uttered. This measure was used in the study by Reeve, Reynolds, Humberstone, and Butterworth (2012), who also recorded children's answers with a digital video camera. The correlation between reaction time measures for the two recording methods was very high (r = .99); therefore, the key press method was considered an efficient way to record reaction time.

Symbolic-to-Analogic Number Transcoding

Two tasks were administered to assess analogic number production from a symbolic number. These tasks involved symbolic number (Arabic or spoken) recognition, as well as production of numerosities in an analogic format. In the Arabic code, an Arabic number (Calibri, 22 millimeters) was presented on the computer screen. In the spoken code, an earphone picture was presented on the computer screen and the children listened to a spoken number. Then they were asked to quickly circle with a pencil (without counting) the corresponding number of dots on a sheet of paper on which a set of one hundred dots in random spatial arrangement was drawn. The participants were not informed that the response sheet comprised 100 dots, to avoid they resort to a proportion strategy. An illustration of the task in each code is presented in Figure 1.

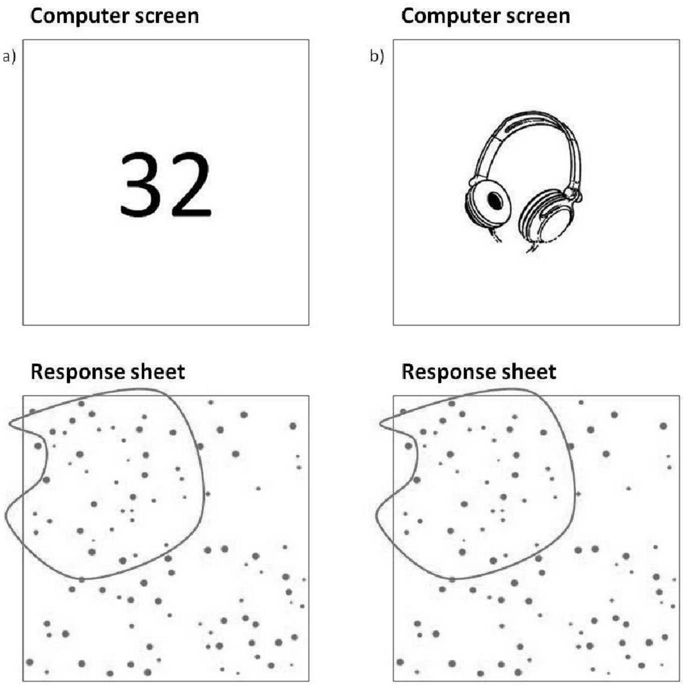

Figure 1. Illustration of the Arabic-to-Analogic Number Transcoding Task (a) and the Spoken-to-Analogic Number Transcoding Task (b).

Arabic and spoken numbers varied from 1 to 99. The 30 numbers varied along three numerical sizes: 10 small numbers from 1 to 4 dots (1, 1, 2, 2, 2, 3, 3, 3, 4, 4) were contrasted with 10 medium numbers from 5 to 9 dots (5, 5, 6, 6, 7, 7, 8, 8, 9, 9) and with 10 large numbers from 10 to 99 dots (12, 17, 26, 31, 46, 53, 64, 79, 85, and 98 for the Arabic code; 11, 19, 24, 33, 48, 52, 65, 76, 87, and 95 for the spoken code). Stimuli were presented in random order. Five practice trials were offered to allow the children to become familiar with the task.

Each trial started with the presentation of symbolic numbers, remaining on the screen until response or until 7000 milliseconds, and followed by a 500-millisecond delay. With respect to the analyses of responses, the ADR was calculated.

Lexical Decision on Symbolic Numbers

Two lexical decision tasks were administered to assess the recognition of symbolic numbers. In the Arabic code, a symbol was presented on the computer screen. In the spoken code, an earphone picture was presented on the computer screen; at the same time, children listened to a spoken symbol. In both tasks, children were asked to decide if the symbol seen or heard was a number or not.

In the Arabic code, stimuli consisted of a white square containing digits (1, 2, 3, 4, 5, 6, 7, 8, 9 presented twice), letters (A, B, C, D, E, F, G, H, J), or mathematical signs (+, -, x, ÷, =, ≠, <, >, //), written in black, for a total of 36 stimuli. In the spoken code, stimuli were digits (1 (/œ̃/), 2 (/dœ/), 3 (/tʁwa/), 4 (/kɑtʁ/), 5 (/sɛ̃k/), 6 (/sis/), 7 (/sɛt/), 8 (/ɥit/), 9 (/nœf/), presented twice), monosyllabic words (en 'in' (/ɛ̃/), beau 'beautiful' (/bo/), bruit 'noise' (/bʁɥi/), pauvre 'poor' (/povʁ/), fonte 'melting' (/fɔ̃t/), fauve 'tawny' (/fov/), chaque 'each' (/ʃɑk/), hyène 'hyena' (/jɛn/), mousse 'foam'(/mus/)), or non-words (u (/y/), ti (/ti/), prui (/pʁɥi/), toupre (/tupʁ/), zonp (/zɔ̃p/), chup (/ʃup/), fat (/fɑt/), hiap (/jap/), mosse /mɔs/) for a total of 36 stimuli. Words and pseudo-words were selected to resemble digit names with respect to number and nature of phonemes as well as syllabic structure. Furthermore, words were controlled in frequency with regard to numbers from the basis Lexique 3 (New et al., 2001).

Stimuli were presented in random order for each participant. Five practice trials were offered to allow the children to familiarize themselves with the task. Each trial started with the presentation of the digit, remaining on the screen until response (in the Arabic code only) or until 4000 milliseconds, and followed by a 500-millisecond delay. Children were asked to respond by pressing the button on the side of the correct response (i.e., on the left green button to answer “yes, it is a digit”, or on the right red button to answer “no, it is not a digit”). Responses were recorded by the computer from the onset of the number word uttered.

Results

Magnitude Comparison of Symbolic Numbers

A 2 (Group: TD vs. MLD) x 3 (Size: Small vs. Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on the mean number of correct responses. The analysis revealed a significant Group effect ($F(1, 59) = 7.700$, $p = .007$, $\eta_p^2 = .115$), indicating that children with MLD were less successful than TD children (TD: Mean (*SD*) = 0.88 (.09); MLD: Mean (*SD*) = 0.86 (.13)). However, there was a marginal Code effect ($F(1, 59) = 3.983$, $p = .051$, $\eta_p^2 = .063$), no Size effect ($F(2, 118) = 0.204$, $p = .815$, $\eta_p^2 = .003$), as well as no interaction ($F(1, 58) = 0.037$, $p = .848$, $\eta_p^2 = .001$ for the Group x Code interaction; $F(2, 116) = 0.221$, $p = .802$, $\eta_p^2 = .004$ for the Group x Size interaction; $F(2, 116) = 0.400$, $p = .671$, $\eta_p^2 = .007$ for the Code x Size interaction; and $F(2, 116) = 0.299$, $p = .742$, $\eta_p^2 = .005$ for the Group x Code x Size interaction). The Group effect disappeared with non-verbal reasoning as well as reading and spelling variables as covariates; it remained significant when each of the other cognitive variables as well as the socioeconomic environment variable were introduced as covariate.

A 2 (Group: TD vs. MLD) x 3 (Size: Small vs. Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANCOVA was performed on response latencies with reaction time as covariate. The analyses revealed no Group effect ($F(1, 58) = 1.846$, $p = .180$, $\eta_p^2 = .031$), a Size effect ($F(2, 116) = 22.978$, $p < .001$, $\eta_p^2 = .284$), a Code effect ($F(1, 58) = 250.103$, $p < .001$, $\eta_p^2 = .812$), but no interaction ($F(2, 116) = 2.508$, $p = .086$, $\eta_p^2 = .041$ for the Code X Size interaction; $F(1, 58) = 2.722$, $p = .104$, $\eta_p^2 = .045$ for the Group X Code interaction; $F(2, 116) = 1.904$, $p = .154$, $\eta_p^2 = .032$ for the Group X Size interaction; and $F(2, 116) = 1.349$, $p = .263$, $\eta_p^2 = .023$ for the Group X Code X Size interaction). Children were faster for small than medium than large numerosities, as well for Arabic than spoken numbers. The mean response latency was 955 milliseconds for Arabic numbers and 3890 milliseconds for spoken numbers.

Magnitude Judgment on Analogic-Symbolic Numbers Association

A 2 (Group: TD vs. MLD) x 2 (Size: Small vs. Medium) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on the mean number of correct responses. The analyses revealed a significant Group effect ($F(1, 59) = 7.174$, $p = .010$, $\eta_p^2 = .108$), indicating that children with MLD were less successful than TD children (TD: Mean (*SD*) = 0.79 (.19); MLD: Mean (*SD*) = 0.73 (.23)). A Size effect ($F(1, 59) = 165.515$, $p < .001$, $\eta_p^2 = .737$) was also observed, but no Code effect (F (1, 59) = 1.989, $p = .164$, $\eta_p^2 = .033$). A Code X Size interaction $F(1, 59) = 4.271$, $p = .043$, $\eta_p^2 = .068$ but no other interaction was observed ($F(1, 59) = 0.819$, $p = .369$, $\eta_p^2 = .014$ for the Group x Code interaction; $F(1, 59) = 0.422$, $p = .518$, $\eta_p^2 = .007$ for the Group x Size interaction; and $F(1, 59) =$

0.365, p = .548, η_p^2 = .006 for the Group x Code x Size interaction). The Group effect disappeared with reading and spelling variables as covariates; it became marginal with non-verbal reasoning and verbal working memory variables as covariates; finally, it remained significant when the other cognitive variables and the socioeconomic environment variable were introduced as covariates.

A 2 (Group: TD vs. MLD) x 2 (Size: Small vs. Medium) x 2 (Code: Arabic vs. Spoken) ANCOVA was performed on response latencies with reaction time as covariate. The analyses revealed a Group effect (F(1, 58) = 8.590, p = .005, η_p^2 = .129), a Size effect (F(1, 58) = 9.484, p = .003, η_p^2 = .141), a Code effect (F(1, 58) = 11.146, p = .001, η_p^2 = .161), but no interaction (F(1, 59) = 0.467, p = .497, η_p^2 = .008 for the Group x Code interaction; F(1, 59) = 0.013, p = .908, η_p^2 < .001 for the Group x Size interaction; (F(1, 59) = 0.742, p = .392, η_p^2 = .012) for the Code x Size interaction; and F(1, 59) = 1.876, p = .176, η_p^2 = .031 for the Group x Code x Size interaction). Children were faster for small than medium numerosities, as well for Arabic than spoken numbers. The mean response latency was 1285 milliseconds for Arabic numbers and 2028 milliseconds for spoken numbers.

Analogic-to-Symbolic Number Transcoding

First, a 2-sample test for equality of proportions, with continuity correction using the prop.test R 3.2.2 (www.r-project.org), was performed in Arabic and spoken modalities for children whose ADR was perfect (i.e. equal to 0) for small numerosities. As expected, the proportion of TD children who got a perfect ADR equal to 0 in Arabic (35/37, 94.6%) and spoken (36/37, 97.3%) code was equivalent to that of children with MLD (Arabic numbers: 22/24, 91.7%; p = 1.000 / Spoken numbers: 21/24, 87.5%; p = .327).

A 2 (Group: TD vs. MLD) x 2 (Size: Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on the ADR. The analysis revealed a significant Group effect (F(1, 59) = 7.804, p = .007, η_p^2 = .117), indicating that the ADR was larger in children with MLD than in TD children (TD: Mean (SD) = 0.17 (.22); MLD: Mean (SD) = 0.23 (.27)), and a significant Size effect (F(1, 59) = 49.70, p < .001, η_p^2 = .457), indicating that the children's ADR was significantly larger for large than medium numerosities. A Code effect was also observed (F(1, 59) = 6.962, p = .011, η_p^2 = .106), indicating that the children's ADR was smaller for spoken than Arabic numbers. No interaction was observed (F(1, 59) = 0.628, p = .431, η_p^2 = .011 for the Group x Code interaction; F(1, 59) = 0.486, p = .489, η_p^2 = .008 for the Group x Size interaction; (F(1, 59) = 1.757, p = .190, η_p^2 = .029) for the Code x Size interaction; and F(1, 59) = 0.057, p = .813, η_p^2 = .001 for the Group x Code x Size interaction). The Group effect disappeared with reading and spelling as covariates, but remained significant when each of the other cognitive variables and the socioeconomic environment variable were introduced as covariate.

A 2 (Group: TD vs. MLD) x 3 (Size: Small vs. Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on response latencies. The analyses revealed no Group effect (F(1, 59) = 1.226, p = .273, η_p^2 = .020), a Size effect (F(2, 118) = 604.237, p < .001, η_p^2 = .911), a Code effect (F(1, 59) = 203.238, p < .001, η_p^2 = .775), a Code x Size interaction (F(2, 118) = 6.832, p = .002, η_p^2 = .104), a Group x Size interaction (F(2, 118) = 3.816, p = .025, η_p^2 = .061), but no other interaction (F(1, 59) = 0.218, p = .642, η_p^2 = .004 for the Group x Code interaction and F(2, 118) = 0.809, p = .448, η_p^2 = .014 for the Group x Code x Size interaction). Children were faster for Arabic than spoken numbers. The mean response latency was 1237 milliseconds for Arabic numbers and 3704 milliseconds for spoken numbers. Post-hoc analysis showed that, in children with MLD, the response latencies were similar for medium and large numerosities (p = 1.000; Glass's Δ = .535), while in TD children, the response latencies were longer for large than for medium numerosities (p < .001; Glass's Δ

= .024). This Group x Size interaction disappeared with reading and spelling as covariates; it became marginal with non-verbal reasoning as covariates; finally, it remained significant when each other cognitive variable and the socioeconomic environment variable were introduced as covariate.

Symbolic-to-Analogic Number Transcoding

First, a 2-sample test for equality of proportions with continuity correction using the prop.test, R 3.2.2 was performed in Arabic and spoken modalities for children whose ADR was perfect (i.e. equal to 0) for small numerosities. As expected, the proportion of MLD children who got a perfect ADR equal to 0 in Arabic (26/37, 70.3%) and spoken (20/37, 54.1%) codes was equivalent to that of children with MLD (Arabic numbers: 12/24, 50.0%; p = .190 / Spoken numbers: 11/24 = 45.8%; p = .715).

A 2 (Group: TD vs. MLD) x 2 (Size: Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on the ADR (see Figure 2). The analysis revealed a significant Group effect ($F(1, 59) = 21.479$, $p < .001$, $\eta_p^2 = .267$), indicating that the ADR was larger in children with MLD, than in TD children, and a significant Size effect ($F(1, 59) = 6.915$, $p = .011$, $\eta_p^2 = .105$), indicating that the children's ADR was significantly larger for large than medium numerosities. No Code effect was observed ($F(1, 59) = 1.006$, $p = .320$, $\eta_p^2 = .017$), indicating that the children with MLD were as successful for Arabic as for spoken numbers. Furthermore, a significant Group x Size interaction was observed ($F(1, 59) = 4.425$, $p = .040$, $\eta_p^2 = .070$). More precisely, post-hoc analysis showed that, in children with MLD, the ADR was similar for medium and large numerosities (p = .737; Glass's Δ = .031), while in TD children, the ADR was larger for large than for medium numerosities (p < .001; Glass's Δ = .733). This Group x Size interaction disappeared with reading and spelling as covariates; it became marginal with non-verbal reasoning and visuospatial working memory as covariates; finally, it remained significant when each other cognitive variable and the socioeconomic environment variable were introduced as covariate.

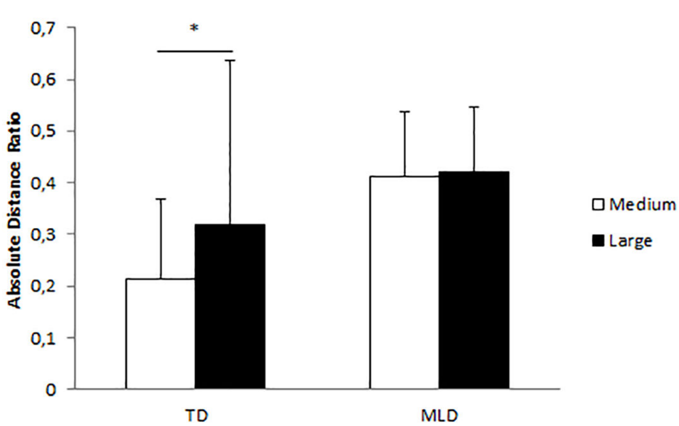

Figure 2. TD and MLD performances on Symbolic-to-Analogic number transcoding tasks (error bars = standard deviation).

A 2 (Group: TD vs. MLD) x 3 (Size: Small vs. Medium vs. Large) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on response latencies. The analyses revealed a marginal Group effect ($F(1, 59) = 3.632$, $p = .062$, $\eta_p^2 = .058$), a Size effect ($F(2, 118) = 127.451$, $p < .001$, $\eta_p^2 = .684$), a Code effect ($F(1, 59) = 50.331$, $p < .001$, $\eta_p^2 = .460$), a Code x Size interaction ($F(2, 118) = 4.716$, $p = .011$, $\eta_p^2 = .074$), but no other interaction ($F(1, 59) = 0.016$, $p = .901$, $\eta_p^2 < .001$ for the Group x Code interaction; $F(2, 118) = 0.514$, $p = .600$, $\eta_p^2 = .009$ for the Group x Size interaction; and $F(2, 118) = 1.038$, $p = .357$, $\eta_p^2 = .017$ for the Group x Code x Size interaction). Children were faster for small than medium than large numerosities, as well for Arabic than spoken numbers. The mean response latency was 2484 milliseconds for Arabic numbers and 5122 milliseconds for spoken numbers.

Lexical Decision on Symbolic Numbers

A 2 (Group: TD vs. MLD) x 2 (Code: Arabic vs. Spoken) ANOVA was performed on the mean number of correct responses. The analyses revealed a significant Group effect ($F(1, 59) = 4.583$, $p = .036$, $\eta_p^2 = .072$) indicating that children with MLD were less successful than TD children (TD: Mean (*SD*) = 0.95 (.08); MLD: Mean (*SD*) = 0.93 (.09)). No Code effect ($F(1, 59) = 3.140$, $p = .082$, $\eta_p^2 = .051$) and no interaction ($F(1, 59) = 1.710$, $p = .196$, $\eta_p^2 = .028$) were observed. The Group effect disappeared with non-verbal reasoning, reading and spelling, and word comprehension and production as covariates; it became marginal with visuospatial short-term memory, as well verbal working memory variables as covariates; finally, it remained significant when processing speed, visuospatial working memory, verbal short term memory, and the socioeconomic environment variable were introduced as covariates.

A 2 (Group: TD vs. MLD) x 2 (Code: Arabic vs. Spoken) ANCOVA was performed on response latencies with reaction time as covariate. The analyses revealed no Group effect ($F(1, 58) = 3.290$, $p = .075$, $\eta_p^2 = .054$), a Code effect ($F(1, 58) = 70.255$, $p < .001$, $\eta_p^2 = .548$), and no interaction ($F(1, 58) < .001$, $p = .994$, $\eta_p^2 < .001$). Children were faster for Arabic than spoken numbers. The mean response latency was 793 milliseconds for Arabic numbers and 1659 milliseconds for spoken numbers.

Discussion

In this study, we investigated the processing of symbolic numbers in children with MLD. In addition to cognitive, linguistic, and mathematic tests, the children were administered experimental tasks involving symbolic number recognition, comprehension, and production designed to answer the following research questions: 1) Do children with MLD present with a deficit affecting Arabic number processing and/or spoken number processing? 2) Do children with MLD present with a deficit affecting number sense access, number production, and/or number recognition? And 3) Is the numerical deficit observed in children with MLD in relation with a more general cognitive deficit?

In summary, results showed that children with MLD had poorer performances than TD children in all symbolic numerical tasks for which moderate and large effect size were found. With respect to the access to number sense from symbolic numbers, children with MLD had lower performances than TD children, regardless of the numerical code, the task, and the size of magnitude. Compared to TD children, children with MLD were also impaired in the production and estimation of medium and large symbolic numbers, regardless of the Arabic or spoken numerical code. In number recognition, they were impaired for Arabic and spoken numbers. This study is the first to show, in the same group of participants, that children with MLD not only presented with an Arabic number processing deficit but also with a spoken number processing deficit and a recognition number deficit. Altogether, results suggested that children with MLD had a general symbolic number processing impairment. Regarding the cognitive capacities, the MLD group was significantly poorer than the TD group for non-verbal reasoning, processing speed, verbal working memory, word comprehension, word production, and reading and spelling.

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With regard to our first research question, our results clearly suggest that MLD is not limited to a specific code but affects both Arabic and spoken symbolic numbers. The present study was thus in line with studies showing that children with MLD had difficulty with Arabic (e.g., De Smedt & Gilmore, 2011) or with spoken numbers (e.g., Olkun et al., 2015). Noël and Rousselle (2011) suggested that MLD is a specific deficit in the access to number sense from Arabic numbers. Results of the present study suggest that this number sense access deficit was observed for Arabic, but also for spoken numbers. In the four-step developmental model of number acquisition (Von Aster & Shalev, 2007), spoken numbers are acquired before Arabic numbers. Therefore, it is logical to assume that impairment in processing spoken numbers, as we reported in this study, could lead to further impairment in processing Arabic numbers. Future studies should address this question.

For the second research question, our results are the first to show that MLD affects number access, number production, and number recognition. First, with respect to number access, our results were in agreement with those reported by De Smedt and Gilmore (2011), Landerl and Kölle (2009), and Rousselle and Noël (2007), who found that children with MLD had difficulty comparing Arabic numbers. Indeed, children with MLD in the present study were less successful and slower than TD children not only in Arabic but also in spoken number comparison and judgment, pointing to a number comprehension deficit in both symbolic codes. Furthermore, children with MLD presented with difficulties in the Magnitude judgment on analogic-symbolic numbers association task, suggesting impairment in mapping non-symbolic numerosities to symbolic numbers. This result was strongly consistent with results recently reported by Wong, Ho, and Tang (2017), who found that Chinese children with MLD also showed deficits in number-magnitude mapping. Overall, our results suggested that children with MLD had a deficit in understanding symbolic numbers and mapping them with numerosities (i.e., number sense).

With respect to number production, our results also confirmed those of studies showing that children with MLD were impaired in tasks consisting of transcoding numerosities in spoken numbers (for example, Olkun et al., 2015; Mazzocco et al., 2011; and Mejias et al., 2012). In the present study, we found that children with MLD were less precise than TD children when asked to produce numbers in both analogic-to-symbolic and symbolic-to-analogic number transcoding tasks. Our results also showed that, compared to TD children, children with MLD were less precise in producing medium and large numerosities in analogic-to-symbolic and symbolic-to-analogic number transcoding tasks. Furthermore, whereas TD children clearly showed better performance to produce medium than large numerosities, it was not the case for children with MLD. These results strongly suggested a deficit in estimation (Feigenson, Dehaene, & Spelke, 2004) and were in agreement with those reported by Mazzocco et al. (2011) and Mejias et al. (2012), who noted impairment in estimating large numerosities in children with MLD. Moreover, children with MLD in our study were not able to identify and transcode medium numerosities in symbolic numbers, in line with what was recently found by Olkun et al. (2015) in 6–10-year-old children. Medium numerosities from 5 to 9 have a particular status because they are frequently met, and they can be subitized and accurately identified through repeated exposure (Clements, 1999). Our results suggested that children with MLD did not adequately develop this capacity to identify medium numerosity by exposition.

Finally, with respect to number recognition, our results pointed to a deficit in recognizing Arabic and spoken numbers in children with MLD. Recognition is a prerequisite for all subsequent number processing abilities. Having difficulty recognizing numbers would thus lead to subsequent impairment in the automatic access to number sense. In other words, a deficit at this processing stage would compromise symbolic number comprehension and production. To our knowledge, this is the first study to show the presence of number recognition impairment in children with MLD.

For the third research question, our results showed that children with MLD also presented with general cognitive difficulties, in addition to mathematical and numerical difficulties. Compared to TD children, they showed lower performance in tests exploring non-verbal reasoning, processing speed, verbal working memory, word comprehension, word production, and reading and spelling. Compared to norms however, no children with MLD presented with a deficit in non-verbal reasoning and processing speed, while two of them presented with a deficit in verbal short-term memory and verbal working memory. Finally, compared to norms, half of the children with MLD presented with a reading and spelling deficit. Most of the Group effects became marginal when the non-verbal reasoning scores were entered as covariates in the analyses. Moreover, most of the Group effects disappeared when the reading and spelling performances were entered as covariates in the analyses. This is not surprising because a high comorbidity of MLD and other developmental deficits such as dyslexia (Barbaresi et al., 2005; Gross-Tsur et al., 1996) or other cognitive deficit such as memory impairment (Geary et al., 2009; Rotzer et al., 2009) has been frequently reported. In the present study, we adopted a practical selection procedure, which reflects the reality existing in clinical and school settings. Therefore, we did not recruit children with isolated MLD and did not exclude children with other learning cognitive and linguistic difficulties. The strict cut-off (-1.5 *SD*) used in the present study allowed identifying children with the most substantial mathematical difficulties, who are also the more at risk of presenting deficits in different cognitive domains. This is also the case in various studies on MLD in which children presented with mathematical difficulties, along with learning, cognitive and/or linguistic impairment (e.g., Ashkenazi, Mark-Zigdon, & Henik, 2013; Andersson & Östergren, 2012; Landerl, 2013). Thus, our results provide support to the hypothesis that MLD is caused by multiple numerical and general cognitive deficits (Geary, 1993, 2010). Our results thus raised the possibility that children with DD may have deficits with symbols, not specifically numerical symbols per se. Taken together, our results clearly show that children with MLD presented with a symbolic numerical processing deficit that could be largely attributed to their poorer written language skills. Future studies should explore how cognitive abilities could influence number sense abilities in children with and without MLD.

In conclusion, the present study showed that children with MLD had poorer performances than those of TD children in all symbolic numerical tasks, regardless of the numerical codes. To our knowledge, this is the first study to show that children with MLD had a symbolic number deficit affecting number access and production abilities, highly suggestive of a deficit in the access to number sense from Arabic, and spoken symbolic numbers. Such a deficit is congruent with results recently reported by Lafay, St-Pierre, and Macoir (2017) who also showed a deficit in the access to the mental number line from Arabic and spoken numbers in children with MLD. Furthermore, they also showed impairment in symbolic number recognition. Thus, these children presented with a deficit affecting the recognition of symbolic numbers, which entailed impairment of symbolic number comprehension and production. With respect to the functional origin of mathematical difficulties, our study also showed that the symbolic numerical processing deficit observed in children with MLD could be largely attributed to their poorer written language skills.

The present study has some implications in guiding effective educational and therapeutic strategies for children with MLD. Teachers and clinicians should better take into account and try to improve symbolic numerical deficiencies in children. A first approach could be to develop exercises and games for the spoken and written counting, building on a constructive and multiple encoding (e.g., song with and without fingers for the spoken

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numbers; drawing and kinaesthetic encoding for the Arabic numbers). Furthermore, teachers and clinicians could strengthen the link between numerical codes (analogical, Arabic and spoken numbers) by systematically presenting numbers in various formats in exercises and games. External representation as concrete objects could be used to illustrate and manipulate symbolic numbers. Some studies (e.g., Osana, Adrien, & Duponsel, 2017) tested such methods in TD children and showed that children benefit from an instruction starting with manipulatives and pursuing with symbolic numbers in understanding of place-value concept and addition algorithm for example. However, it remains unclear if they would be helping for children with MLD, so that future studies are required.

The present study has some limitations. First, children were allowed to provide a response within many seconds (4 seconds in Judgment tasks; 7 seconds in transcoding tasks), although they were explicitly asked to answer as quickly as possible. Several examples were also given to encourage children to proceed as fast as possible and to prevent them from counting. Moreover, children answered within 1749 ms for small numerosities and 2028 ms for medium numerosities in judgment task. Such response latency made it highly unlikely the use of a counting strategy. Such response latencies are congruent with Mandler and Shebo (1982) who showed that small and medium numerosities were subitized within two seconds. Longer latencies were however recorded (2484 ms for small numerosities to 5122 ms for large numerosities) in the transcoding tasks, due to the nature of the tasks requiring the production of a written or spoken response. Despite these precautions and observations, we cannot completely rule out the possibility that some children had adopted a counting strategy while others actually had "subitized" numerosities. In further research, very short presentation of stimuli should be preferred in order to avoid counting in subitizing assessment. Finally, another limit specifically concerned the Symbolic-to-analogic number transcoding task in which children were asked to estimate the magnitude represented by the Arabic or the spoken numbers on the screen by quickly circling with the pencil the same number of dots on a sheet of paper. However, the number of dots on the sheet of paper (i.e. 100) and the numbers presented on the computer screen (varying from 1 to 99) allowed only the production of underestimation errors. In further studies, tasks allowing for under- and over-estimation errors should be used to better assess analog number production.

The present study begs various other research questions. Further studies should first examine how the development of Arabic numbers is independent of or linked to the development of spoken numbers. According to the developmental model of number acquisition (Von Aster & Shalev, 2007), Arabic numbers are acquired after spoken numbers and impairment of Arabic number processing could be the consequence of impairment of spoken number processing. This assumption needs to be tested. In our study, both symbolic codes are affected in children with MLD and further studies are needed to disentangle the two processes. Moreover, further studies should investigate how symbolic number deficits are implied in different mathematical difficulties in children with MLD and, more precisely, which is the implication of Arabic number processing and that of spoken number processing. Studies with younger children in a longitudinal paradigm could be useful in examining these questions. Also, future studies should examine what effects number deficits in children with MLD have on the development of the mental number line. According to the developmental model of number acquisition (Von Aster & Shalev, 2007), the three steps (analogic, spoken, and Arabic number processes) are necessary preconditions for the fourth step, which consists of developing a mature mental number line. One could legitimately ask, therefore, if symbolic number impairment in children with MLD has an impact on their numerical mental representation, and more specifically on their mental number line.

Supplementary Materials

The underlying data for this article can be found at: https://doi.org/10.7910/DVN/FCHKAU

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Competing Interests

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Ethics Approval

This study was approved by the Research Ethics Committee of the Research Centre of the Institut universitaire en santé mentale de Québec.

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