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Impairment of Non-Symbolic Number Processing in Children With Mathematical Learning Disability

Anne Lafay[ab], Marie-Catherine St-Pierre[a], Joël Macoir*[ab]

[a] Department of readaptation, Université Laval, Quebec City, Canada. **[b]** CERVO Brain Research Centre, Quebec City, Canada.

Abstract

The functional origin of Mathematical Learning Disability (MLD), an impairment affecting mathematics learning, remains controversial. We aimed to study the number sense deficit hypothesis in children with MLD. We explored the processing of non-symbolic numbers in Quebec French-speaking 8–9-year-old children with three non-symbolic tasks (number comparison, number matching and dot set selection task). Results showed that children with MLD were as successful as typically developing children in a comparison task, but less successful in a matching task. Their performance in numerical re-production was also similar to that of typically developing children for large (10-99) numerosities, while they were less successful in transcoding small (1-4) and medium (5-9) numerosities. Children with MLD also presented with general cognitive and reading difficulties. Results suggest a deficit in processing small and medium numerosities in children with MLD that could be largely attributed to their poorer cognitive skills.

Keywords: mathematical learning disability, dyscalculia, number sense, numerosity, non-symbolic numerals

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*Corresponding author at: Department of readaptation, Pavillon Ferdinand-Vandry, 1050, avenue de la Médecine, Local 4295, Université Laval, Quebec City, Canada. E-mail: joel.macoir@fmed.ulaval.ca

Mathematics is involved in many activities of daily life, such as counting sets of objects, using time or distance measures, handling money, saying oral numbers, and even writing and reading Arabic numbers (e.g., phone numbers). Although they are abstract in nature, people easily – and even automatically – perceive, use, and manipulate numbers in everyday life. Furthermore, poor numeracy is an important cause of educational under-achievement (Fortin, Royer, Potvin, Marcotte, & Yergeau, 2004). 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 Mathematical Learning Disability (MLD), is defined as a disorder that interferes with mathematics learning and daily life activities. MLD is manifested by mathematics difficulties affecting various abilities such as counting, enumeration, calculation, problem-solving, etc. Studies on MLD to date showed a remarkable prevalence from 1 to 10% depending on the cut-off score established by the researchers (e.g., Badian, 1999; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005).

The cognitive processing of numbers has been conceptualized in various theoretical models. In the triple-code model (Dehaene, 1992, 2010), three different representations are used for number processing skills in adults. Numbers may be manipulated and represented mentally in three different codes: analogical, Arabic, and verbal. The Arabic (e.g., 3) and verbal (e.g. /three/) codes are both symbolic and asemantic, while the analogical code is non-symbolic and represents the magnitude of numerosities over a number line (other said the number sense). According to the literature, this number line is spatially oriented from left to right (Hubbard, Piazza, Pinel, & Dehaene, 2005) and is compressive so that the space between pairs of numbers becomes smaller as numerical magnitude increases (Izard & Dehaene, 2008). This code is required to process number comparisons or approximate calculations, for example. Number sense is an inherited system of numerical processing based on core-system representation of magnitude, which allows the child to process subitizing and estimation (von Aster & Shalev, 2007). Subitizing and estimation abilities rely respectively on the precise numerical system (also called Object Tracking System, OTS) and the Approximate Numerical System (ANS) (see Feigenson, Dehaene, & Spelke, 2004 for a description of these systems and processes). The OTS sustains subitizing, which is the intuitive, fast, and precise ability to enumerate small sets of objects, without counting. The OTS is limited to 3 to 6 (Krajcsi, Szabó, & Mórocz, 2013; Schleifer & Landerl, 2011; Starkey & Cooper, 1995). For its part, the ANS sustains estimation, which is the intuitive, fast, and approximate ability to enumerate large sets of more than 5 objects, without counting. Numerosities from 5 to 9 have a particular status because, although they depend on the ANS, they can be subitized and precisely identified through exposition and learning (Clements, 1999; Sullivan & Barner, 2014). According to von Aster and Shalev (2007) and Feigenson, Dehaene, and Spelke (2004), both the OTS and ANS are important for developing arithmetic abilities. Other researchers, such as Carey (2001, 2004) and Butterworth (1999, 2005), postulated that only the OTS is essential for understanding cardinality of sets. According to Carey (2001, 2004), the cardinality is related to the relation between the knowledge of the list of number-words and the object–file representations.

The triple-code model (Dehaene, 1992, 2010) and the four-step developmental model of number acquisition (von Aster & Shalev, 2007) are in agreement with respect to the functional origin of MLD. According to the triple-code model, MLD is a “number sense” deficit resulting from an impaired analogical code while, according to the four-step developmental model of number acquisition, it results from an impairment of the inherited core-system representation of magnitude. Such a deficit would lead to difficulty processing non-symbolic number representations and impaired mental numerical representations, and would therefore cause problems in the comparison, identification and estimation of numbers. In the majority of studies, the ability to compare non-symbolic numbers was impaired in children with MLD (Landerl, Fussenegger, Moll, & Willburger, 2009; Mazzocco, Feigenson, & Halberda, 2011; Skagerlund & Träff, 2014), whereas this impairment was not reported in some other studies (De Smedt & Gilmore, 2011; Landerl & Kölle, 2009; Rousselle & Noël, 2007). Moreover, the results of a meta-analysis suggest that the deficits in non-symbolic number processing in MLD would be related to the children‘s age (De Smedt, Noël, Gilmore, et al., 2013). In their literature review, Noël, Rousselle, and De Visscher (2013) also support this assumption and reported that 8- to 14-year-old children with MLD showed impairment of number sense while this ability was preserved in 6- to 10-year-old children with MLD. In the present study, non-symbolic number processing was explored in 8- to 9-year-old children.

Finally, there is also no clear consensus regarding the presence of a deficit affecting the OTS and/or ANS in children with MLD. Some studies suggested an OTS deficit because these children were not able to identify precisely and quickly small numerosities (Andersson & Östergren, 2012; Ashkenazi, Mark-Zigdon, & Henik, 2013; Landerl, 2013; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Schleifer & Landerl, 2011). In most of these studies, children were asked to say, as quickly as possible, how many dots were presented on a computer screen. However, this task not only involves a non-symbolic numerical process, but also a symbolic process since children had to give the response orally. Therefore, such a task does not allow the symbolic and non-symbolic aspects of number processing to be disentangled. Another task was also used by Castro Cañizares et al. (2012) who asked children to quickly compare pairs of small numerosities from 1 to 4 presented on a computer screen and to select the one that contained the most elements. However, this task did not include numerosities superior to 4, while the OTS is limited to 5 (Schleifer & Landerl, 2011; Starkey & Cooper, 1995) and even 6 (Krajcsi, Szabó, & Mórocz, 2013). Sella, Lanfranchi, and Zorzi (2013) adopted a specific paradigm to avoid the influence of symbolic processing in the assessment of subitizing. They developed a dots-to-dots match-to-sample task in which children with Down syndrome were asked to report whether target dot sets had the same or a different numerosity with respect to a sample dot set. However, until now no similar task had been used in children with MLD. With respect to the ANS, Castro Cañizares, Reigosa Crespo, and González Alemañy (2012) found good performances in processing large numerosities in 9–10-year-old children with MLD. In other behavioral studies, these children had less precise number acuity in non-symbolic comparison tasks involving large numerosities (Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010). Number acuity refers to the precision of the internal numerical representation and the performance is assessed as a function of the ratio between the to-be discriminated numerosities. Although an increasing number of studies in recent years have documented this aspect in MLD, the presence of a deficit affecting the OTS and/or ANS remains unclear. This issue is addressed in the present study. The present study thus assessed the OTS in a completely non-symbolic design using three experimental tasks: non-symbolic number comparison task, non-symbolic number matching task, and dot set selection task. In the non-symbolic number comparison task, the participant has to identify the largest of two numerical magnitudes represented with dots. This task, which is the most frequently used in studies (Schneider, Thompson, & Rittle-Johnson, 2018), is a classic, “pure”, and valid measure of non-symbolic number abilities (Dietrich, Huber, & Nuerk, 2015). Moreover, it is correlated with mathematical competence and is predictive of mathematical competence over time (see the systematic qualitative literature review from De Smedt, Noël, Gilmore, & Ansari, 2013; see the narrative review from Schneider, Thompson, & Rittle-Johnson, 2018). In the non-symbolic number matching task, the participant is required to decide if two numerical magnitudes are equal or not. This other measure of number sense abilities (Dietrich, Huber, & Nuerk, 2015; Gebuis & van der Smagt, 2011; Sasanguie, Defever, Van den Bussche, & Reynvoet, 2011; Smets, Gebuis, Defever, & Reynvoet, 2014) is cognitively more demanding than the comparison task since it requires a response between two possible choices. This additional difficulty is observed in adults who are less successful in matching than in comparison tasks (Smets et al., 2014). Moreover, as pointed out by Smets et al. (2015), the participants’ performance is influenced by the method that is used to construct the arrays of dots in these kinds of tasks. Therefore, a dot set selection task was used in the present study. In the dot set selection task, the participant is asked to estimate the numerosity represented by the dots on the screen by quickly circling with the pencil (without counting) the same number of dots on the sheet of paper. This original task requires more engagement and seems more direct since the expected response is supposed to reflect the numerosity the children have activated following the stimulus presentation.

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). Some researchers claimed that MLD is related to a number sense deficit per se (Wilson & Dehaene, 2007), whereas others argued that MDL is due to a number sense access deficit (Noël & Rousselle, 2011). Furthermore, 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, Bailey, Littlefield, 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). The present study thus included an assessment of the cognitive abilities of children in terms of language, reading, memory, speed processing, and reasoning.

In summarize, a number sense deficit was hypothesized to explain the mathematics difficulties observed in MLD. However, there is still no consensus regarding the actual existence of such a deficit or the presence of a deficit affecting the OTS and/or ANS. In the present study, we investigated the number sense deficit hypothesis in children with MLD through an assessment of their abilities to process non-symbolic numerosities. More precisely, this study addressed the following research questions: 1) Do children with MLD present with a number sense deficit? 2) Do children with MLD present with a specific deficit affecting the OTS necessary to subitize very small numerosities or the ANS necessary to estimate large numerosities? And 3) Is the numerical deficit observed in children with MLD in relation with cognitive and/or written language 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. 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.

Seventy-six 8- or 9-year-old third grade French-speaking children were recruited for this study. In summary, there were 37 TD children (mean age in months = 107.3, *SD* = 3.8, min = 100, max = 113) and 24 children with MLD (mean age = 108.2, *SD* = 4.3, min = 102, max = 118). The participants are those of the study of Lafay, St-Pierre, and Macoir (2017) and Lafay, Macoir, and St-Pierre (2018). As described in detail in these previous papers, our results showed that children with MLD also presented with general cognitive difficulties (based on tests of non-verbal reasoning, processing speed, language, reading, verbal and visuospatial memory), in addition to mathematical and numerical difficulties. The presence of MLD was based on a cut-off score of -1.5 *SD* on the Zareki-R test (Dellatolas & Von Aster, 2006) and was determined according to the DSM-5 (2013) which indicates that “low achievement scores on one or more standardized tests or subtests within an academic domain (i.e., at least 1.5 standard deviations [*SD*] below the population mean for age) are needed for the greatest diagnostic certainty” (section 315). The performance of the MLD group indeed was significantly poorer than that of the TD group for non-verbal reasoning, processing speed, verbal working memory, word comprehension, word production, reading and spelling. 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 reading and spelling deficit.

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, a display and response collection software (Forster & Forster, 2003).

Non-Symbolic Number Comparison Task

This task was administered to assess analogical number comparison. It is a classic, “pure”, and valid measure of non-symbolic number abilities (Dietrich, Huber, & Nuerk, 2015). Two sets of dots were presented on the computer screen and the children were asked to select the one that contained the most dots. There are several visual properties that covary with numerosity. For example, visual properties such as the occupied area, cumulative surface area, item size, total circumference, and density of the items are usually considered in comparison tasks (Dietrich et al., 2015). It was physically impossible to control for all properties at the same time. In the present study, we chose to control for the occupied area and cumulative surface area, as done in the majority of studies (Leibovich & Henik, 2013). With respect to the occupied area, stimuli consisted of pairs of black squares (10-cm sides) separated by a 2-cm space and containing a set of blue (left stimulus) or yellow (right stimulus) dots. The dots were not of equal size, so that the cumulative surface area was identical for both sets of dots and was controlled by a program developed by Price, Palmer, Battista, and Ansari (2012). Magnitude comparisons were performed on 30 pairs in which the number of dots varied from 1 to 99. These pairs varied along three numerical sizes: 8 small pairs with 1 to 4 dots, 7 medium pairs with 5 to 9 dots, and 15 large pairs with 10 to 99 dots. Furthermore, the pairs also varied along three ratios of dots: 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 a pair of dot sets, remaining on the screen until response or until 4000 milliseconds, and followed by a 500-millisecond delay. Responses and latencies were recorded by the computer. Blue and yellow stickers were stuck respectively 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 on the screen, the children were asked to respond by pressing the button on the side of the correct response (i.e., the largest number).

Non-Symbolic Number Matching Task

This non-symbolic number matching task is another measure of estimation abilities (Dietrich, Huber, & Nuerk, 2015; Gebuis & van der Smagt, 2011; Sasanguie, Defever, Van den Bussche, & Reynvoet, 2011; Smets, Gebuis, Defever, & Reynvoet, 2014). Two sets of dots were presented on the computer screen and the children were asked to decide if they represented the same numerosity or not. Compared to a non-symbolic number comparison task, the non-symbolic number matching task is cognitively more demanding (Dietrich, Huber, &

Nuerk, 2015) since it requires a response between two possible choices. As shown by Dietrich et al. (2015), adults are less successful in matching than in comparison tasks, suggesting that the first is more difficult.

Stimuli consisted of pairs of black squares (10-cm sides) separated by a 2-cm space and containing a set of blue (left stimulus) or yellow (right stimulus) dots. The occupied area and cumulative surface area were identical for both sets of dots and controlled by a program developed by Price, Palmer, Battista, and Ansari (2012). Magnitude judgments were performed on 18 pairs in which the number of dots varied from 1 to 9. These pairs varied along two numerical sizes: 9 small pairs with 1 to 4 dots, and 9 large pairs with 5 to 9 dots. Furthermore, 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. Half of the pairs were identical, and half were different. The side on which the largest number was presented in pairs with a different number of dots 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 a pair of dot sets, remaining on the screen until response or until 4000 milliseconds, and followed by a 500-millisecond delay. Responses and latencies were recorded by the computer. Green and red stickers were stuck respectively on the left Alt key and right Alt key of the keyboard. As this task required choosing between two possible responses (“yes, the two numerosities are identical” or “no, the two numerosities are different”), one displayed on the left and one displayed on the right side on the screen, the 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”; on the right red button to answer “no”).

Dot Set Selection Task

This dot set selection task is another measure of estimation ability. It was administered to assess analogical number production. As with the two other experimental tasks, the dot selection task also involved attentional visuospatial abilities. In comparison and matching tasks, the integrity of non-symbolic numerosities is derived from the ability to make judgments on presented stimuli. In comparison, a dot set selection task requires more engagement and seems more direct since the expected response is supposed to reflect the numerosity the children have activated following the stimulus presentation. This task allows estimation abilities to be measured without involving counting. The children were given a pencil and sheet of paper on which a set of 100 dots was drawn. A set of dots was then presented on the computer screen and they were asked to estimate the numerosity represented by the dots on the screen by quickly circling with the pencil (without counting) the same number of dots on the sheet of paper. This task is illustrated in Figure 1.

This dot set selection task was performed on 30 sets in which the number of dots varied from 1 to 99. These sets varied along three numerical sizes: 10 very small numerosities with 1 to 4 dots (1, 1, 2, 2, 2, 3, 3, 3, 4, 4), 10 small numerosities with 5 to 9 dots (5, 5, 6, 6, 7, 7, 8, 8, 9, 9), and 10 large numerosities with 10 to 99 dots (12, 17, 26, 31, 46, 53, 64, 79, 85, 98). 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 dot set, remaining on the screen until response or until 7000 milliseconds, and followed by a 500-millisecond delay.

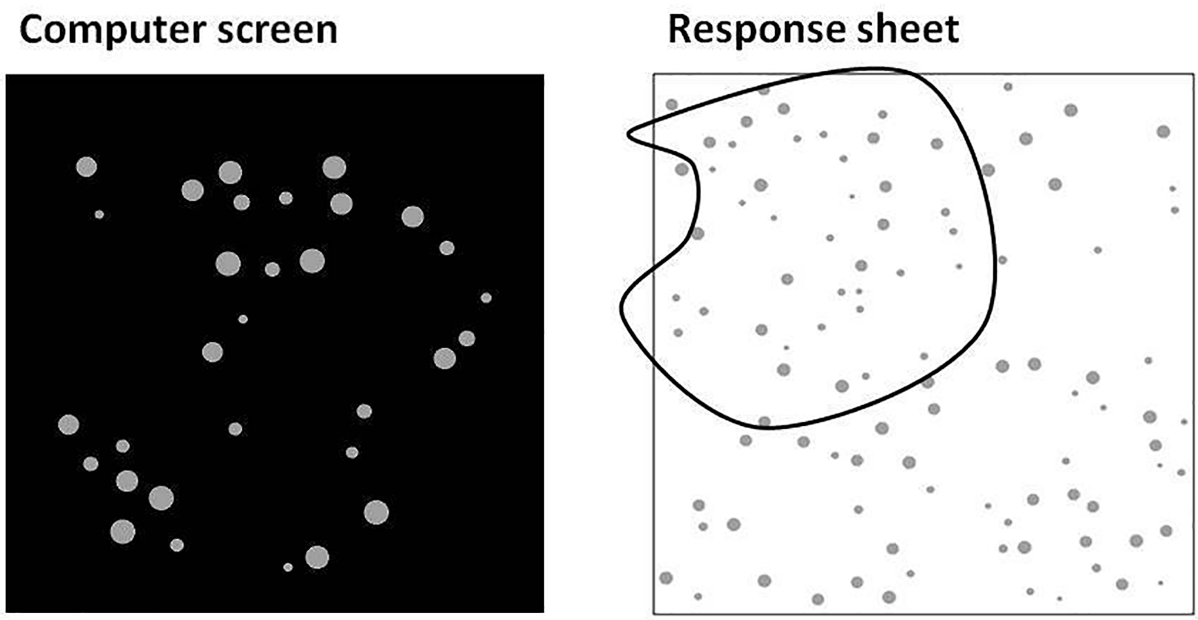

Figure 1. Illustration of the dot set selection task.

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 the analyses. Therefore, a ratio (child's response / target number) between the 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 ratio (ADR) between the child's calculated ratio and the perfect ratio 1 was calculated: ADR = 1 – child's response / target number. The experimenter and a research assistant separately counted each dot. In case of disagreement, they corrected the response sheet together until they reached complete agreement. All the dots positioned under the line drawn by the children were counted. Finally, response time was also recorded by the experimenter, who pressed a response key as soon as the child started his/her response. 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.

Results

Non-Symbolic Number Comparison

The analyses were performed to identify the differences between TD and MLD children in terms of numerical accuracy and processing speed in function of numerosity size and the ratio between the two numerosities.

A 2 (Group: TD vs. MLD) x 3 (Numerosity: Small vs. Medium vs. Large) ANOVA was performed on the mean number of correct responses (see Table 1). For the mean number of correct responses, the children with MLD were as successful as the TD children, $F(1, 59) = 2.467$, $p = .122$, $\eta_p^2 = .040$. However, the analysis did reveal a Numerosity effect, $F(2, 118) = 52.957$, $p < .001$, $\eta_p^2 = .473$, indicating that children were less successful for large than medium numerosities ($p < .001$), and for medium than small numerosities ($p < .001$). No interaction was observed, $F(2, 118) = 1.183$, $p = .310$, $\eta_p^2 = .020$.

Table 1

Mean Number of Correct Responses and Mean Response Latencies (SD) on Three Non-Symbolic Numerical Tasks for TD and MLD

		TD (*n* = 37)		MLD (*n* = 24)	
Size of Numerosity	**Measure**	***M***	***SD***	***M***	***SD***
Comparison					
Small	Responses	.94	.06	.94	.07
Small	Latencies	1205.91	225.89	1236.18	175.29
Medium	Responses	.89	.07	.85	.14
Medium	Latencies	1244.00	235.77	1273.70	253.87
Large	Responses	.82	.08	.78	.10
Large	Latencies	1148.31	227.97	1167.59	208.86
Total	Responses	.88	.09	.86	.13
Total	Latencies	1199.41	231.21	1225.82	216.61
Matching					
Small	Responses	.89	.12	.86	.14[a]
Small	Latencies	1392.37	266.90	1506.60	227.36
Medium	Responses	.69	.20	.59	.23[a]
Medium	Latencies	1512.29	292.94	1492.58	392.91
Total	Responses	.79	.19	.73	.23[a]
Total	Latencies	1452.33	284.77	1499.59	317.64
Selection					
Small	ADR	.05	.12	.17	.19[a]
Small	Latencies	2945.46	557.13	2837.15	455.28
Medium	ADR	.35	.25	.61	.49[a]
Medium	Latencies	3750.63	1028.99	3361.09	942.02
Large	ADR	.40	.11	.42	.15
Large	Latencies	3948.71	1204.85	3785.25	1199.91
Total	ADR	.27	.23	.40	.36[a]
Total	Latencies	3548.27	1055.05	3327.83	986.67

[a]These ability scores were significantly lower than those of TD children ($p < .05$) or these ADRs were significantly larger than those of TD children ($p < .05$).

A 2 (Group: TD vs. MLD) x 3 (Numerosity: Small vs. Medium vs. Large) ANCOVA was performed on response latencies (with reaction time as covariate). The children with MLD were as fast as the TD children, $F(1, 58) = 0.005$, $p = .943$, $\eta_p^2 < .001$. However, the analysis did reveal a significant Numerosity effect, $F(2, 116) = 3.499$, $p = .033$, $\eta_p^2 = .057$. Post-hoc analysis (with Bonferroni correction) showed that the children were faster for large than for small ($p = .012$) and medium ($p < .001$) numerosities. However, they were as fast for medium as for small numerosities ($p = .097$). No interaction was observed, $F(2, 116) = 0.290$, $p = .749$, $\eta_p^2 = .005$.

Furthermore, a 2 (Group: TD vs. MLD) x 3 (Ratio: 1/2 vs. 2/3 vs. 3/4) ANOVA was performed on the mean number of correct responses for all stimuli regardless of their numerical size; a 2 (Group: TD vs. MLD) x 3 (Numerosity: Ratio: 1/2 vs. 2/3 vs. 3/4) ANCOVA was also performed on response latencies for all stimuli regardless of their numerical size. Results showed a Ratio effect for the mean number of correct responses, $F(2, 118) = 44.984$, $p < .001$, $\eta_p^2 = .433$, and for the response latencies, $F(2, 116) = 4.075$, $p = .019$, $\eta_p^2 = .066$. Post-hoc analysis (with Bonferroni correction) showed that children were more successful for the ratio 1/2 than the ratio 2/3 ($p < .001$) and 3/4 ($p < .001$) and that they were faster for the ratio 1/2 than the ratio 2/3 ($p < .001$) and 3/4 ($p < .001$). However, there was no Group x Ratio interaction for the mean number of correct responses, $F(2, 118) = 0.429$, $p = .652$, $\eta_p^2 = .007$, or for the response latencies, $F(2, 116) = 0.123$, $p = .884$, $\eta_p^2 = .002$.

Non-Symbolic Number Matching Task

First, we performed a correlation analysis to verify that our tasks captured the same construct. We observed a significant correlation respectively between the number of correct responses ($r = .485$) and between the latencies ($r = .650$) in comparison and matching tasks.

Second, the following analyses were performed to identify the differences between TD and MLD children in terms of numerical accuracy and processing speed in function numerosity size and the ratio between the two numerosities.

A 2 (Group: TD vs. MLD) x 2 (Numerosity: Small vs. Medium) ANOVA was performed on the mean number of correct responses (see Table 1). For the mean number of correct responses, the children with MLD were less successful than the TD children, $F(1, 59) = 4.918$, $p = .018$, $\eta_p^2 = .091$; large size effect. Children were more successful for small than medium numerosities, $F(1, 59) = 149.528$, $p < .001$, $\eta_p^2 = .717$. No interaction, $F(1, 59) = 2.503$, $p = .119$, $\eta_p^2 = .041$, was observed. The Group effect remained significant when the visuospatial and verbal short-term and working memory and word comprehension and production variables, as well as the socioeconomic environment variable were introduced as covariates, although it disappeared with the non-verbal reasoning, processing speed, reading and spelling as covariates.

Third, a 2 (Group: TD vs. MLD) x 2 (Numerosity: Small vs. Medium) ANCOVA was performed on response latencies (with reaction time as covariate) (see Table 1). The analysis revealed no Group effect, $F(1, 58) = 0.29$, $p = .865$, $\eta_p^2 = .001$. Children were faster for small than medium numerosities, $F(1, 58) = 4.523$, $p = .038$, $\eta_p^2 = .072$. No interaction, $F(1, 58) = 1.982$, $p = .164$, $\eta_p^2 = .033$, was observed.

Furthermore, a 2 (Group: TD vs. MLD) x 3 (Ratio: 1/2 vs. 2/3 vs. 3/4) ANOVA was performed on the mean number of correct responses for different pairs, and a 2 (Group: TD vs. MLD) x 3 (Numerosity: Ratio: 1/2 vs. 2/3 vs. 3/4) ANCOVA was performed on response latencies (with performance in reaction time task as covariate) for all stimuli regardless of their numerical size. Results showed no Ratio effect for the mean number of correct responses, $F(2, 118) = 0.833$, $p = .437$, $\eta_p^2 = .014$, or for the response latencies, $F(2, 116) = 1.543$, $p = .218$, $\eta_p^2 = .026$), and no Group x Ratio interaction for the mean number of correct responses, $F(2, 118) = 0.149$, $p = .862$, $\eta_p^2 = .003$, or for the response latencies, $F(2, 116) = 1.339$, $p = .266$, $\eta_p^2 = .023$.

Dot Set Selection Task

First, we performed a correlation analysis between the latencies of each task to verify that our tasks captured the same construct. It was not possible to do a correlation analysis between the mean number of correct responses in the comparison and matching tasks and the ADR of the dot set selection task because of the nature of the data. The latencies in the dot set selection task were significantly correlated with the latencies in the comparison task ($r = .350$), as well with the latencies in the matching task ($r = .420$).

Second, the following analyses were performed to identify the differences between TD and MLD children in terms of numerical accuracy and processing speed in function of numerosity size.

A 2 (Group: TD vs. MLD) x 3 (Numerosity: Small vs. Medium vs. Large) ANOVA was performed on the ADR (see Table 1). The ADR was larger in the MLD group than in the TD group, $F(1, 59) = 10.015$, $p = .002$, $\eta_p^2 = .145$; large effect size. A significant Numerosity effect, $F(2, 118) = 47.140$, $p < .001$, $\eta_p^2 = .444$, was observed. Furthermore, a significant Group x Numerosity interaction was observed, $F(2, 118) = 4.517$, $p = .013$, $\eta_p^2 = .071$; moderate effect size. More precisely, post-hoc analysis (with Bonferroni correction) showed that in MLD, the ADR was larger than in TD children for small ($p = .006$) and medium numerosities ($p = .008$), although the two groups did not differ for large numerosities ($p = .535$). The main Group effect was still significant when each cognitive variable (except reading and spelling), as well as the socioeconomic environment variable, was introduced as covariate; the Group x Numerosity interaction were still significant when verbal working memory and reading and spelling were introduced as covariates but became marginal with other cognitive variables as covariates (non-verbal reasoning, processing speed, verbal short-term memory, word comprehension and production, visuospatial short-term and working memory, and socioeconomic environment).

Third, a 2 (Group: TD vs. MLD) x 3 (Numerosity: Small vs. Medium vs. Large) ANCOVA was performed on the response latencies (with reaction time as covariate) (see Table 1). TD children took between 2017 ms and 4100 ms for the small numerosities, between 1850 ms and 5835 ms for the medium numerosities and between 2168 ms and 5760 ms for the large numerosities. MLD children took between 1970 ms and 3942 ms for the small numerosities, between 2013 ms and 4738 ms for the medium numerosities and between 1916 ms and 5626 ms for the large numerosities. The analysis revealed no Group effect, $F(1, 57) = 1.208$. $p = .276$, $\eta_p^2 = .021$, but a significant Numerosity effect, $F(2, 114) = 6.544$, $p = .002$, $\eta_p^2 = .103$. Post-hoc analysis (with Bonferroni correction) showed that the children were significantly faster for small than medium ($p < .001$) and large numerosities ($p < .001$), and faster for medium than large numerosities ($p < .001$). No interaction was observed, $F(2, 114) = 0.742$, $p = .478$, $\eta_p^2 = .013$.

Discussion

In this study, we investigated the number sense deficit hypothesis in children with MLD through an assessment of their abilities to process non-symbolic numerosities. In addition to cognitive, linguistic and mathematical tests, the children were administered three experimental tasks of non-symbolic number processing (non-symbolic number comparison task, non-symbolic number matching task, and dot set selection task) designed to answer the following research questions: 1) Do children with MLD present with a number sense deficit? 2) Do children with MLD present with a specific deficit affecting the OTS necessary to subitize very small numerosities or the ANS necessary to estimate large numerosities? And 3) Is the numerical deficit observed in children with MLD in relation with cognitive and/or written language deficit?

In summary, results showed that the children with MLD had performances that were as good as those of the TD children in non-symbolic number comparison, but they were less successful than the TD children in non-symbolic number matching, regardless of whether the numerosities depended on the OTS or ANS. In that task, children with MLD showed a large effect size impairment. Furthermore, children with MLD were less successful than TD children in producing small and medium non-symbolic numerosities in the dot set selection task and the difference corresponded to a large effect size. However, their performances were as good as those of the TD children in producing large non-symbolic numerosities. These results first showed that children with MLD did not have a general number sense deficit since their performance was affected only in some of the tasks or for some sizes of numerosities. Instead, they suggest that MLD could be a specific deficit affecting number sense. 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.

Our results are not in line with the propositions (e.g., Davidse, de Jong, Shaul, & Bus, 2014; Desoete, Ceulemans, De Weerdt, & Pieters, 2012) related to the origin of MLD based on the triple-code model and/or the four-step developmental model of number acquisition. In all these studies, researchers measured non-symbolic abilities with comparison tasks only. To the best of our knowledge, the present study was the first to explore, in the same group of children, the processing of analogical numbers in three different experimental tasks. In our study, children with MLD showed difficulties in the non-symbolic number matching task, but not in the non-symbolic number comparison task. This result is in agreement with some studies, which showed that the ability to compare non-symbolic numbers was efficient in children with MLD (De Smedt & Gilmore, 2011; Landerl & Kölle, 2009; Rousselle & Noël, 2007). However, other researchers found that this ability was impaired in these children (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009). In our study, the difference between the results obtained in these two tasks could be explained by their differential cognitive load. First, Smets et al. (2015) showed better performance in adults when the visual cues of the dot arrays corresponded to the presentation area (i.e., the largest area comprising the most dots and vice versa) in comparison tasks. In the present study, there was always congruency between the number of dots and the area surface in the comparison task. This could have made the task easier to process than having included sets of dots with pairs matching in total area and pairs matching in density, for example. Furthermore, Smets et al. (2015) explained that participants' performance is influenced by the method that was used to construct the arrays of dots in comparison tasks making it difficult to compare studies in which such tasks were used. Compared to the comparison task in which the children had to give an answer that was consistent spatially with the location of the stimulus (i.e., if the largest number was on the right or on the left of the screen, children had to click on the right or on the left button respectively), the non-symbolic number matching task required additional cognitive processes involving working memory and inhibitory control (Dietrich, Huber, & Nuerk, 2015). Indeed, the matching task required a response between two possible choices and arbitrarily imposed that the "yes" was the left button and the "no" the right button, so that children had to keep this information in working memory. As shown in the present study, children with MLD showed a deficit in processing speed and verbal working memory. Further studies should explore how executive functions are involved in non-symbolic number matching and how children with MLD are impaired in executive functions, for example. Furthermore, another explanation could be given with regards to the three ratios used in the comparison and matching tasks (1/2, 2/3 and 3/4). Considering the age of the children, the large size of numerosities, and the fact that stimuli were displayed up to four seconds, these ratios were maybe too easily discriminable, even for children with MLD. Therefore, it was possible that the non-symbolic number comparison task, which was less cognitively demanding, lacked the sensitivity to detect an ANS deficit in children with MLD.

With respect to the second issue addressed by our study, our results showed that children with MLD were less successful than TD children in producing small numerosities (1-4), suggesting the alteration of subitizing abilities depending on the OTS. This result was in line with Castro Cañizares, Reigosa Crespo, and González

Alemañy (2012), who noted a subitizing deficit in 9–10-year-old children with MLD but was not in accordance with Desoete and Grégoire (2006), who found that only 33% of 8–10-year-old children with mathematical difficulties had difficulty processing small numerosities. Unlike Mazzocco, Feigenson, and Halberda (2011) and Piazza et al. (2010), who showed that children with MLD had less precise number acuity in a non-symbolic comparison task of large numerosities, we observed good performances in the production of large numerosities (10-99), suggesting preservation of estimation and approximation abilities relying on the ANS. In our opinion, the discrepancy between results could be explained by the use of different tasks and the various methods used to analyze the children's responses in production (i.e. calculation of the mean ratio in comparison and selection tasks). More interestingly, in our study, children with MLD had difficulty producing medium numerosities (from 5 to 9), a result suggesting that they were not able to subitize and precisely identify these numerosities, as TD children did by exposition and learning (Clements, 1999). Our results suggest that the ANS was preserved in children with MLD, but these children had an OTS deficit. They confirmed that the OTS is essential for mathematics development (Carey, 2001, 2004; Butterworth, 1999, 2005). Furthermore, these results challenged the existence of the OTS and the ANS, the two numerical core systems respectively devoted to the processing of small (1-4) and large (5-99). They rather supported the propositions of Feigenson, Dehaene, and Spelke (2004), according to which a single numerical system, precise for small numerosities and more approximate when numerosities grow, sustains the processing of all numerosities. Future studies are needed to confirm the hypothesis of a unique processing system for all non-symbolic numerosities.

For the third research question, our results showed that children with MLD also presented with 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, 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. Half of the children with MLD presented with a reading and spelling deficit. Furthermore, the Group effect for the non-symbolic number matching task disappeared when the non-verbal reasoning, the processing speed, and the reading and spelling performances were entered as covariates in the analyses. The main Group effect was still significant when each cognitive variable (except reading and spelling), as well as the socioeconomic environment variable, was introduced as covariate. They besides presented with deficit to process with symbolic numbers (Lafay, Macoir, & St-Pierre, 2018; Lafay, St-Pierre, & Macoir, 2017). First, 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 executive control impairment (Geary, Bailey, Littlefield, et al., 2009; Rotzer et al., 2009) has been frequently reported. Furthermore, Ashkenazi and Silverman (2017) recently indicated that multiple factors can affect mathematics performance (processing speed, perception, sustained attention, reading). 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). The fact that the children in the current study presented with cognitive deficits could explain why our results were not always in line with former research that failed to show a number sense deficit. Thus, our results suggest that MLD is caused by multiple numerical and cognitive deficits, as proposed by Geary (1993, 2010). Taken together, our results clearly show that children with MLD presented with a non-symbolic numerical processing deficit that could be largely attributed to their poorer cognitive skills. Future studies should explore how cognitive abilities could influence number sense abilities in children with and without MLD.

The results of the present study suggest that children with MLD aged from 8 to 9 years old did not have a general number sense deficit: their ANS was preserved, whereas they presented with impairment of the OTS leading to difficulty processing of small and medium numerosities. Noël, Rousselle, and De Visscher (2013) reported that 8- to 14-year-old children with MLD showed impairment of number sense while this ability was preserved in 6- to 10-year-old children with MLD. The use of three different tasks in the present study allows to nuance this conclusion and give more precision, that is the preservation of the ANS but the impairment of the OTS in children with MLD aged from 8 to 9 years.

The present study has some implications in guiding effective educational and therapeutic strategies for children with MLD. The number sense underlies human mathematical knowledge and is at the heart of mathematics learning. Therefore, teachers and clinicians should better take into account and try to improve non-symbolic numerical deficiencies in children. Over the past years, some studies aimed to train the number sense, especially the ANS, with the intention of transferring improvements to symbolic arithmetic. In their literature review, Szűcs and Myers (2017) however concluded that there is no conclusive evidence that specific ANS training improves symbolic arithmetic. As shown in the present study, children with MLD rather presented with impairment of the OTS, leading to difficulty processing of small and medium numerosities. Future studies are then required to investigate if OTS training would be beneficial to children with MLD and would help improve their abilities in symbolic arithmetic.

The present study has two main limitations. First, the research sample was heterogeneous since we adopted a practical selection procedure, reflecting the reality existing in clinical and school settings. Therefore, the group of children with MLD included children with pure MLD and children with MLD associated with other cognitive deficits. Our conclusions must be cautiously interpreted with respect to the functional origin of pure MLD. Second, children were allowed to provide a response within many seconds (4 seconds in comparison and matching tasks; 7 seconds in dot set selection task) although they were explicitly asked to answer as quickly as possible. Several examples were also given to encourage the children to proceed as quickly as possible and prevent them from counting. Moreover, children answered within 1236 ms for small numerosities, 1273 for medium numerosities, and 1168 ms for large numerosities in the comparison task. This response latency made the use of a counting strategy highly unlikely. Such response latencies are congruent with Mandler and Shebo (1982), who showed that small and medium numerosities were subitized within two seconds. Similar response latencies were also recorded in the matching task for small and medium numerosities. However, longer latencies (2837ms, 3361ms and 3948ms for small, medium and large numerosities respectively) were recorded in the dot set selection task, due to the nature of the task which required the production of a written response. Despite these precautions and observations, we cannot completely rule out the possibility that some children adopted a counting strategy while others actually "subitized" numerosities. In further research, very short presentation of stimuli should be used to avoid counting in subitizing assessment.

In sum, the results of the present study suggest that children with MLD did not have a general number sense deficit: their ANS was preserved, whereas they presented with impairment of the OTS leading to difficulty processing of small and medium numerosities. With respect to the functional origin of mathematical difficulties, our study also showed that the non-symbolic numerical processing deficit observed in children with MLD could be largely attributed to their poorer cognitive skills. This result challenges the four-step developmental model of number acquisition, according to which MLD is an impairment of the inherited core-system representation of magnitude. Hence, our results suggest that, in MLD children, the number sense deficit specifically affects the OTS, thus confirming that this system is essential for mathematics development (Carey, 2001, 2004). Future research should explore the impact of the OTS impairment on the processing of symbolic numbers as well as on the development of a mature mental number line, the next steps in the developmental model of number acquisition.

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Competing Interests

The authors have declared that no competing interests exist.

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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.

Data Availability

For this study, a dataset is freely available (see the Supplementary Materials section).

Supplementary Materials

The underlying data for this article, including stimuli, raw data, and response time can be found at: https://doi.org/10.23668/psycharchives.2373

Index of Supplementary Materials

Lafay, A., St-Pierre, M.-C., & Macoir, J. (2019). *Supplementary materials to "Impairment of non-symbolic number processing in children with mathematical learning disability".* PsychOpen. https://doi.org/10.23668/psycharchives.2373

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