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Symbolic and Non-Symbolic Number Magnitude Processing in Children with Developmental Dyscalculia

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The aim of this study was to evaluate if children with Developmental Dyscalculia (DD) exhibit a general deficit in magnitude representations or a specific deficit in the connection of symbolic representations with the corresponding analogous magnitudes. DD was diagnosed using a timed arithmetic task. The experimental magnitude comparison tasks were presented in non-symbolic and symbolic formats. DD and typically developing (TD) children showed similar numerical distance and size congruity effects. However, DD children performed significantly slower in the symbolic task. These results are consistent with the access deficit hypothesis, according to which DD children's deficits are caused by difficulties accessing magnitude information from numerical symbols rather than in processing numerosities *per se*.
Keywords: size congruity effect, distance effect, dyscalculia, reaction time, size effect.

El objetivo de este estudio fue evaluar si los niños con Discalculia del Desarrollo (DD) presentan un déficit general en la representación de las magnitudes o un déficit específico en la conexión de las representaciones simbólicas con sus correspondientes magnitudes análogas. La DD fue diagnosticada mediante una tarea aritmética con control del tiempo de reacción. Las tareas experimentales de comparación de magnitudes se presentaron en formato no-simbólico y simbólico. Los resultados muestran que en los discalcúlicos la representación numérica parece estar intacta, lo cual se expresa en efectos de distancia numérica y congruencia de la magnitud, similares a los que exhiben los niños con un desarrollo típico. Las diferencias respecto a este grupo se encuentran solo en la velocidad de procesamiento en las tareas simbólicas. Se concluye que los datos se ajustan a la hipótesis del déficit en el acceso, por lo que las dificultades de los niños discalcúlicos parecen producto de un trastorno en la conexión entre las representaciones simbólicas y las análogas y no en la representación numérica *per se*.
Palabras clave: discalculia, efecto de distancia, efecto de congruencia de la magnitud, efecto de magnitud, tiempo de reacción.

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At present, experimental evidence shows that our mathematical competence emerges from the interaction between two dissociable representational systems (Barth, La Mont Lipton, & Spelke, 2005; Halberda, Mazzocco, & Feigenson, 2008): a system of approximate quantities (common to animals, babies and adults) and a verbal system capable of representing numbers exactly (Dehaene, 1997). It has been suggested that in the approximate number system, the quantities are represented in an analogue format, similar to an internal "number line", which is shared by the different sensory modalities (Butterworth et al., 1999, Dehaene, 1997; Halberda et al., 2008; Izard & Dehaene, 2008; Paterson, 2001; Udwin, Davies, & Hosylin, 1996). Evidence from research on infants supports the assumption of the inherent and innate nature of this system (Dantzig, 1967, Dehaene, 1997).

Once language is acquired, humans develop (within an appropriate cultural context) the ability to represent numerosities in a symbolic format, first using number words (for example "thirty-three") and later using Arabic digits (Dehaene & Marques, 2002, Gallistel & Gelman, 2005, Moyer & Landauer, 1967, Spelke & Tsivkin, 2001). This enables them to access a new level of competence in exact arithmetic. Apparently, the increasing dominance of a symbolic number system influences the improvement of previously acquired skills for handling non-symbolic numerical quantities (Pica, Lemer, Izard, & Dehaene, 2004).

Several current cognitive theories on developmental dyscalculia (DD) suggest that the origin of this disorder may be a deficit in one of the representational systems described above. These theories assume that subtle deficiencies in the core systems of numerical representation, or in the connection between them, can generate a cascade of new deficits in the development of high-level skills such as addition and multiplication (Karmiloff-Smith, 1998). However, currently, there is still no consensus on what exact deficit underlies this learning disorder.

Two of the theories that propose that DD may be caused by damage to the numerical representation are the "number sense" hypothesis (Dehaene, 1997; 2001) and the "defective number module" hypothesis (Butterworth, 1999; 2005). S. Dehaene suggests that we have two core knowledge systems with "numerical content": 1) an approximate representation system, which allows to extract the approximate numerosity of the stimuli or to represent them as analogous magnitudes, and, 2) an "object file" system. This is an attentional system that allows "the exact representation of different elements" (up to 3 or 4 objects) (Carey, 2001; Feigenson, Dehaene, & Spelke, 2004; Wilson & Dehaene, 2007; Simon, 1999; Xu & Spelke, 2000). As consequence of the visuospatial nature of non-symbolic tasks, a deficit in the latter system could lead to difficulties in subitizing (which is the basic numerical ability that allows instant and accurate estimation of amounts of up to four visually presented elements, Mandler & Shebo, 1982), and generally, in the perception of non-symbolic numerical information. However, in the deficit in number sense as the underlying cause of DD proposal, it is assumed that the deficit is in the analogous system. According to this idea, children with DD would show difficulties in the ability to represent continuous quantities (analogue and approximate representation of quantity) and to relate them to word lists that designate integers, which allows the development of representations for discrete quantities greater than four. Therefore, DD children can present deficits in understanding the meaning of numbers, difficulties in tasks related to this domain (non-symbolic tasks such as approximate comparison and dot addition and also for symbolic comparison, addition and subtraction tasks), and difficulties in the magnitude spatial representation within the mental number line (Butterworth, 2010). These deficits would prevent a normal development of numerical concepts (Ashkenazi, Mark-Zigdon, & Henik, 2009).

On the contrary, unlike the deficits in number sense hypothesis, B. Butterworth (1999, 2005, 2010) suggests that DD results from deficits in the representation of exact numerosities (discrete quantities in a set) that generate difficulty in understanding the concept of number and, consequently, in the learning of numerical information. Although this might seem like a simple extension of the encoding of small numbers, no upper quantity limit or attentional role is assumed (Butterworth, 2010). According to this hypothesis, subjects can perform normally in approximate numerosity and analogous magnitude tests (Butterworth, 1999, 2005, Butterworth & Reigosa-Crespo, 2007; Landerl, Bevan, & Butterworth, 2004).

Several behavioural evidences support that DD's difficulties in number comparison and in subitizing may be the result of a disorder in numerical representation, as children with DD are slower than typically developing children (TD) in digit naming and subitizing, but not in letter and geometric figure naming (Landerl, Fussenegger, Moll, & Willburger, 2009; van der Sluis, de Jong, & van der Leij, 2004). Also, DD children have shown a significantly lower performance than normal children in basic number processing tasks that include reading and comparison of non-symbolic and symbolic quantities, repeating numbers sequences and/or dot counting (Iuculano, Tang, Hall, & Butterworth, 2008; Landerl et al., 2004; Landerl et al., 2009; Landerl & Kölle, 2009; Mussolin, Mejias, & Nöel, 2010). It has also been reported that children with DD show persistent difficulties in learning simple addition and subtraction strategies, which suggests a reduced comprehension of number meaning or the ability to manipulate numbers (Wilson & Dehaene, 2007).

Other elements supporting predictions of a deficit in number representation in DD are the difficulties in the automatic processing of quantities when these are presented using number words and digits (Dehaene, 1997, 2001; Wilson & Dehaene, 2007). These difficulties are expressed in a reduced size congruency effect (interference between physical and numerical size of the numerosities to be compared) and even in the non-appearance of such effect in numerical Stroop tasks. Landerl et al., (2004) found no congruency effect in 8 and 9 year-old DD children. Similar results were obtained by Landerl and Kölle (2009) when evaluating eight to ten year-old DD children (second, third and fourth grades). Rubinsten and Henik (2005, 2006) reported a reduced congruency effect even in young adults with DD.

The above data support the deficit in numerical representation hypothesis (either approximate or exact representations) as the underlying cause of DD. However, this theory was challenged by Rousselle and Nöel (2007) who proposed the "access deficit" hypothesis, as they believe that DD arises from a disconnection syndrome between non-symbolic quantity representation (which remains intact) and the symbols that denote these analogous magnitudes (digits or number words). Neuropsychological and brain imaging data indicate that there is an association between exact arithmetic tasks and language codes (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999, Lemer, Dehaene, Spelke, & Cohen, 2003), so that when we learn the numerical symbols, we simply learn to "map" arbitrary shapes to the relevant representation of non-symbolic quantity. If this connection does not develop adequately, even when the numerosity representation remains intact, DD will appear as result of a deficit in accessing the numerical meaning of symbols. In this way, DD children would be able to make non-symbolic magnitude comparisons, but would fail when comparing the same quantities presented in symbolic format (for example, Arabic digits).

In order to validate the "access deficit" hypothesis, Rousselle and Nöel (2007) evaluated a group of children with DD (selected through an untimed battery of arithmetic achievement tasks) using quantity comparison tasks presented in symbolic (digits) and non-symbolic (pairs of collections) format. For the collection comparison tasks, two conditions with perceptual control (density and surface) were designed, which allowed to ensure that the subjects' judgments were made based on numerical information (discrete quantities) and not on the perceptual features of the stimuli that covary with numerosity (continuous quantities). The results showed that children with mathematical disabilities performed normally in all non-symbolic tasks (which implies that the basic numerical concepts are intact), but, in the digit comparison symbolic task, their results were significantly different (they were slower and less accurate) that those for the TD group. Similarly, when the individual processing speed was adjusted in the symbolic Stroop task, DD children showed a congruency effect such as that found for TD children, however, they needed more time for the appearance of physical differences to interfere with their numerical judgement. The authors concluded that the mathematical learning disorder is not a result of a difficulty in numerosity representation, but rather a deficit in accessing the numerical representation from a symbolic format (Rousselle & Nöel, 2007). These results were later replicated by Iuculano et al., (2008) using the comparison between symbolic and non-symbolic (with area control) tasks of quantity comparison in children with and without DD. Most recently, de Smedt and Gilmore (2011) also replicated these results using comparison and approximate addition tasks (presented in both formats) in children with regular mathematic achievement, children with low achievement in mathematics and children with mathematics learning disabilities.

Although much experimental evidence supports the hypotheses discussed above, the results diverge across the research, arriving at conclusions in favour of either hypothesis. These differences may be due to methodological reasons in the experimental design. For example, the batteries of experimental tasks are not always designed to assess, in the same sample, several of the classic numerical processing effects (numerical distance, numerical size and size congruency), but are generally aimed at evaluating only one of those effects. Sometimes the experimental designs do not include paired tasks in both symbolic and non-symbolic format.

It is worth mentioning that different sample selection criteria have been used across the experimental studies: untimed arithmetic achievement tests (Rousselle & Nöel, 2007), neurocognitive batteries with mathematical fluency tasks with limited runtime (Landerl et al., 2009; Landerl & Kölle, 2009; Mussolin, Mejias, & Nöel, 2010), item-timed mental arithmetic test (Landerl, Bevan & Butterworth, 2004), or standardized software that combines basic numerical ability sub-scales and arithmetic tasks (Iuculano et al., 2008).

Multiple studies suggest that the selection of DD children should be made through basic numerical processing tasks controlling for reaction time (RT) (Butterworth & Reigosa-Crespo, 2007; Feigenson, Carey, & Spelke, 2002; Landerl et al., 2004) because RT measurements can show abnormalities that accuracy cannot reveal (Butterworth, 2005; Jordan & Montani, 1997). Arithmetic tasks with RT control are probably a very sensitive indicator for DD diagnosis (Mussolin et al., 2010). The difficulties in higher-level arithmetic processes (counting acquisition and addition procedure disorders, as well as in numerical facts retrieval) may be derived from an initial dysfunction in the core numerical processing system, even when other causes are plausible (Dehaene, Bossini, & Giraux, 1993; Desoetea, Ceulemansa, Roeyersa, & Huylebroeck, 2009; Jordan, Hanich, & Kaplan, 2003; van Loosbroek, Dirkx, Hulstijn, & Janssen, 2009; Xu & Spelke, 2000). Moreover, there is consensus in considering the calculation fluency deficit as one of the distinguishing features of DD children (Barnes et al., 2006; Geary & Hoard, 2005; Jordan & Montani, 1997).

The aim of this study is to evaluate whether a group of children with DD (diagnosed through an item-timed mental arithmetic test) have a general deficit in magnitude representation (whether it is a deficit in number sense or in numerical module), or a difficulty linking symbolic representations onto their corresponding analogous magnitudes. Unlike previous studies, a battery of experimental tasks, where each task designed in symbolic format (Arabic digits comparison, physical size of digits comparison, symbolic Stroop tasks) is contrasted with a equivalent one designed in a non-symbolic format (collections comparison, physical size of geometric shapes comparison, non-symbolic Stroop -the latter has hardly ever been included in previous designs-see Iuculano et al., 2008) was used in this study. To avoid subjects using strategies based on low-level continuous (perceptual) variables in the non-symbolic magnitude comparisons, three sets of collections with different perceptual controls were generated: surface, density and area.

This design will allow us to evaluate the effects of numerical distance, numerical size and size congruency in each presentation format. Studies carried out with TD children have not been able to identify a modulation of the congruency effect by numerical distance, and this issue has not yet been examined in DD children (Landerl & Kölle, 2009). The modulation of the congruency effect by the numerical size has not been either evaluated. In this regard, the present study evaluates the automatic processing of quantities according to the modulation of the congruency effect by the numerical size for the non-symbolic format (since stimuli were designed only for large numerical distances-see section "Non-symbolic Tasks"-), and the modulation of the congruency effect by distance and numerical size in the symbolic format.

Two other issues distinguish this design from previous studies. Firstly, RT of correct responses of each experimental condition were adjusted with data of the simple RT task. In this way, the time the subjects may have used in other processing different from numerical processing (i.e. motor execution) is eliminated from the RT obtained in the experimental task. This method has been previously used by Iuculano et al., (2008). Secondly, in each analysis, the scores obtained in the backward digit span were included as covariates. It has been reported that numerical knowledge is strongly correlated with measures of working memory obtained through the backward digit span (Chard et al., 2005). In this regard, several studies indicate that DD children tend to have a less developed working memory capacity than TD children (Geary, Brown, & Samaranayake, 1991; Geary, Hamson, & Hoard, 2000; Geary, Hoard, & Hamson, 1999; Koontz & Berch, 1996, McLean & Hitch, 1999; Swanson & Beebe-Frankenberger, 2004; Siegel & Ryan, 1989; Wilson & Swanson, 2001). These evidences suggest that different working memory difficulties can co-occur with mathematical deficits, so it is necessary to control this variable in studies with DD children. Despite this evidence, most studies do not consider this important covariation.

The access deficit hypothesis predicts the existence of difficulties in processing symbolic patterns that denote analogous magnitudes, whereas a deficit in magnitude representation may reflect a strong inaccuracy in numerical representation, regardless of the stimuli presentation format. Manipulations between the presentation format, the size, numerical distance, and size congruency enable the search for new evidence regarding both hypotheses. If DD is a disorder in the development of a cognitive system that underlies the processing of numerical quantities (Butterworth, 1999; Butterworth & Reigosa-Crespo, 2007; Dehaene, 1997, 2001), we expect that DD children will show difficulties in all numerical comparison tasks, regardless of the presentation format with respect to TD children. In addition, we expect that they will show no sign of automatic number processing. On the contrary, if DD children have a specific problem in accessing the symbolic representation of numbers (as suggested by Rousselle & Nöel, 2007), they must have difficulty in symbolic processing, but show a similar performance to TD children in the tasks where analogous magnitudes are processed. Moreover, they must show automatic activation of the semantic properties of quantities when these are presented under conditions adapted to their symbolic processing speed.

Method

Participants

The sample of this study is a sub-group of a population of 226 school-aged children, which participated in a mathematical disabilities prevalence study that was carried out in Havana city, Cuba (Reigosa-Crespo et al., 2012). Initially, all children with signs of behavioural disorder risk were excluded from the sample. To be included in the TD group, children should show no sign of learning disorders (according to the Signs of at-Risk Learning Disabilities Questionnaire (SRD-L)), and to be included in the DD group, children should show, at least, one sign of learning disorders (according to SRD-L). The Ravens Colored Progressive Matrices Test (Raven, Court, & Raven, 1992) was administered to all the selected children as an intellectual performance measure (nonverbal reasoning ability). The scores were analyzed according to the Chilean norms (Ivanovic et al., 2000). Children who had scores between the 50th and 95th percentile were selected. The arithmetic achievement of this group was evaluated through The Arithmetic Mental Test developed by Reigosa and colleagues (Reigosa-Crespo et al., 2012).

Children that scored above 1.5 standard deviations (*SD*) in The Arithmetic Mental Test, were included in the TD group ($N = 33$), and children with scores below 2 *SD* were included in the DD group ($N = 32$). The 65 children finally selected were administered the Digit Span Scale (forward

Table 1
Sample Details

Group		Age (years)	Raven (scores)	Forward Digit Span (scores)	Backward Digit Span* (scores)	Arithmetic Mental Test**(EM)
TD	*M*	9.52	28.39	5.85	4.61	109.1
(*N* = 33)	*SD*	.27	3.94	1.75	1.41	26.31
DD	*M*	9.49	27.22	6.03	3.84	194.49
(*N* = 32)	*SD*	.32	3.62	1.40	1.25	85.5

Significant differences between TD and DD group: **$p < .001$, * $p < .05$

and backward) of the Wechsler Intelligence Scale for Children (Revised) (WISC-R) (Sattler, 1982), that assesses phonological short-term memory and working memory. Sample details are described in Table 1.

Materials and Procedure

Arithmetic Mental Test: Item-timed computerized test, which included 15 simple additions, 15 subtractions, and 15 multiplications, was presented in three separate blocks. Two practice trials were given before the start of each block. All arithmetic operations involved single-digit numbers (from 1 to 9). Items were presented on a computer screen in the form "2 + 4". Children were asked to type the answer as quickly as they could without making any mistakes. To answer, children used the number keypad to the right of the alphanumeric keypad. Reaction time was recorded when the key corresponding to the calculated number was pressed. All responses, both correct and incorrect were recorded. Median RTs for correct responses in all tasks (addition, subtraction and multiplication) were calculated. The medians were adjusted, subtracting each one from the median of the simple RT for that participant (adjRTs). This procedure enables the adjustment of RT to the individual variability in processing speed. It has been noted that children with low numeracy tend to adopt strategies that produce generally accurate answers but extremely long RT latencies (see also Jordan & Montani, 1997); or that they simply guess quickly, leading to inaccurate answers but short RT latencies. For this reason, similar to the procedure described by Landerl, Bevan and Butterworth (2004), an efficiency measure (EM) for each test was calculated by diving adjRTs by the proportion of hits (EM = adjRT/Hits). This is an inverse measure (higher EM scores represent worse performance). The mean of EM scores for each operation (addition, subtraction, and multiplication) was used as an overall measure of efficiency in the mental arithmetic test. The software diagnoses DD based on norms calculated for each age group. Therefore, the children who had an EM below 2 *SD* on the mental arithmetic test regarding the normative sample were classified as dyscalculic.

Experimental Tasks

The experimental tasks were run using the stimulus presentation software SuperLab 4.0 for Windows XP/2000. Children were always asked to respond by pressing the button on the side of the correct response (right or left). Instructions emphasized both speed and accuracy. The computer automatically recorded the RT of each response. Each task was preceded by 8 training trials. The battery of experimental tasks was administered in two sessions of 30-40 min. In a first session, the Simple Reaction Time Task was applied and then, the remaining comparison tasks were applied in counterbalanced order. In a second session, Stroop tasks were administered.

Simple Reaction Time Task: Some children are relatively slow in pressing keys when responding to any stimuli. The Simple Reaction Time test was designed to evaluate this achievement. The score on this test was not analyzed by itself. Instead, the RTs of the remaining experimental tasks (described below) were adjusted taking this measure into account (see statistical analysis section). Children were presented with a blue circle over a white background. This blue circle was counterbalanced across trials, appearing to the left or the right side of the screen. Children were asked to press the key corresponding to the side where the circle appeared. Each trial started with the presentation of a blue circle until a response was given, followed by inter-stimulus interval that varied between 100 and 1500 ms (white screen).

Non-symbolic Tasks

Collection Comparisons: Children were simultaneously presented with two white squares (side = 55 mm) containing a variable number of vertical black rectangles or small blue squares, and were instructed to select the one that contained more elements. Both white squares were presented on a dark grey background and were separated by a fixation cross (distance between squares = 8 mm).

The task was administered in three intermixed conditions of perceptual control: density, surface and area (see Table 2 for details of perceptual control in each set). Rousselle,

Table 2
Controlled perceptual features for collection comparison tasks in each set

Set	Perceptual Variables						
	Density[a]	External contour length[b]	Total Area Occupied on the Screen	Total Surface (area/ brightness)[c]	Total Perimeter[d]	Element Size	Distance between elements[e]
Density	*					*	
Surface		*	*	*	*		
Area			*	*			*

The asterisk (*) indicates the perceptual variable is controlled.
[a] The proportion of occupied positions on the screen divided by the total number of possible positions.
[b] Perimeter delineated by external elements of the collection.
[c] Sum of the area of all elements of the collection.
[d] Sum of perimeter of all elements of the collection.
[e] Distance between the elements of the collection (never less than 8 pixels).

Palmers and Noël (2004) designed the density and surface condition stimuli, and small numerosities (between 1 and 4) were not included in these arrays. These authors pointed out that small numerosities (subitizing range) are supposed to be apprehended by different quantification processes from counting and approximated estimation of large numerosities (Simon, 1997; Trick & Pylyshyn, 1994) and therefore, it could not reflect the typical characteristics of the comparison process. In spite of this, in the area condition, arrays with numerosities between 1 and 4 were also included. In this way, all numerosities can be compared with the symbolic task and the corresponding analyses of numeric size effect can be carried out. In the three conditions, the numerical distances were of 1 (close distances) and, 3 or 4 (far distances).

The task consisted of a total of 96 items: (3 density-controlled collection pairs + 3 surface-controlled collection pairs) X 2 distances X 4 presentations + (3 area-controlled collection pairs X 2 size X 2 distances X 2 sides X 2 presentations) (see details in Castro, Estévez, & Pérez, 2011). Each trial started with the presentation of a collection pair until a response was given, followed by an ISI of 500 ms during which the fixation cross remained in full view.

Physical Size Comparison: Children were presented with two identical geometric shapes and were asked to select the larger physical size. (e.g. small circle: 166 mm of diameter and larger circle: 184 mm of diameter). The side of correct response was counterbalanced across the left or the right side of the screen. The six geometric shape pairs used (circles, triangles, rectangles, squares, ellipses and rhombus) were presented four times, twice with the larger shape on the right and twice with the larger shape on the left, yielding a total of 24 pairs of geometric shapes to be compared (6 pairs x 2 sides x 2 presentations). Each trial started with the presentation of a shape pair until a response was given, followed by an ISI of 500 ms (white screen). The results of this task were not analyzed *per se*. The medians of these RT were used to calculate a variable delay in the non-symbolic Stroop task.

Stroop: The Stroop tasks (symbolic and non-symbolic) were designed to examine the presence of signs indicating automatic processing of the irrelevant numerical dimension (numerical size) in each group.

Schwarz and Ischebeck (2003) proposed a relative speed account of the number-size interference in non-symbolic Stroop tasks. In accordance with their model, the decisions are not based on all-or-none information, rather in the partial information that continuously accumulates until the decision is reached. As both processing types (numerical size and physical size) are influenced by distance, the processing of the relevant and irrelevant dimensions is influenced by the distance (e.g., the physical and the numerical distance), to increase numerical interference over physical decision, difficulty physical comparison could be increased (e.g. collection pairs with similar physical size) or the numerical comparison could be facilitated (e.g. collection pairs with far numerical distance). In accordance with this proposal, we selected the stimuli with area control and far numerical distance (3 or 4). The collection pairs varied between two dimensions: numerical size and physical size. Each trial started with the presentation of a collection pair of same physical size (sum of total area of all elements = 56 mm^2) and different numerical size. Each collection pair was presented four times, two in ascending order and two in descending order, yielding a total of 48 collection pairs to be compared (3 collection pairs X 2 sizes X 2 congruencies X 2 presentations).

To balance the speed of physical and numerical processing, a variant of the procedure proposed by Rousselle & Nöel (2007) was used. Thus, the physical size difference between digits only appeared after a delay variable. This delay was individually calculated by computing, for each participant, the difference between his/her median of RT needed to perform a physical size comparison (same geometrical shapes, different size) and his/her median of RT required to compare collections of the area condition (different numerosities, same size). The difference in milliseconds was rounded to the upper hundred. After the delay, the physical size difference between collections emerged: in one of them, the sum of total area of all elements increased (81 mm^2) and, in the other, it decreased (36 mm^2). Children were asked to choose the side with "more blue", ignoring numerical size. Collection pairs were presented until a response was given, followed by an ISI of 500 ms (white screen).

Symbolic Tasks

Arabic Number Comparison: Two Arabic digits from 1 to 9 (Arial, 48-point font) were presented on the computer screen and children were asked to select the largest digit in numerical size. Comparison pairs varied along two numerical sizes and two distances between digits: small pairs (digits from 1 to 5) were contrasted with large pairs (digits from 5 to 9) and close pairs (distance of 1) were compared with far pairs (distance of 3 or 4). Three different pairs of digits were used in each experimental sub-condition, yielding a total of 48 pairs of single-digit number to be compared (3 digit pairs X 2 sizes X 2 distances X 2 sides X 2 presentations) (for more details see Rousselle & Nöel, 2007). Each trial started with the presentation of a digit pair until a response was given, followed by an ISI of 500 ms (white screen).

Physical Size Comparison: Children were presented with two identical Arabic digits (on a white screen) and were asked to select the largest digit in physical size (e.g., 2–2, Arial, 65 pt or 72 pt). The six digit pairs used were presented in a fixed pseudo-random order. The side of the correct response was counterbalanced. The six digit pairs (2–2, 3–3, 4–4, 6–6, 8–8, and 9–9) were presented four times, twice with the larger digit on the right and twice with the larger digit on the left, yielding a total of 24 pairs of digits to be compared (6 pairs X 2 sides X 2 presentations). Each trial started with the presentation of a digit pair until a response was given, followed by an ISI of 500 ms (white screen). The results of this task were not analyzed *per se*. The medians of these RT were used to calculate a variable delay in the symbolic Stroop task.

Stroop task: Children were presented with pairs of Arabic digits (1–9) varying along two dimensions: physical and numerical size. Congruency between the physical and the numerical dimensions was manipulated: in congruent pairs, the largest digit in physical size was also the largest in numerical size (e.g., 2 4), while in incongruent trials, the largest digit in physical size was the smallest in numerical size (e.g., 2 4). In both conditions (congruent and incongruent), the same digit pairs as those used in Arabic number comparison were included, yielding a total of 96 pairs of digits to be compared (3 digit pairs X 2 numerical sizes X 2 distances X 2 sides X 2 congruity conditions X 2 presentations) (for more details see Rousselle & Nöel, 2007).

Each trial started with the appearance of a pair of digits presented in the same intermediate physical size. The physical size difference between digits appeared after a delay variable. This variable was computed using the procedure described by Rousselle & Nöel (2007): for each participant, his/her median RT in the physical size comparison task (same digits, different size) was subtracted from his/her median RT in the Arabic number comparison task (different digits, same size). In this way, numerical and physical information are equally likely to influence the decision process, more effectively conditioning that numerical information (irrelevant dimension) interferes in physical comparison (relevant dimension) (Noël, Rousselle, & Mussolin, 2005).

The difference in milliseconds was rounded to the upper hundred. After the delay, the physical size difference between digits emerged with one digit increasing in size (72 pt) and the other one decreasing (65 pt). Children were asked to select the largest digit in physical size, ignoring numerical size. Digit pairs were presented until a response was given, followed by an ISI of 500 ms (white screen).

Statistical analysis

RT analyses were performed with the median RT of correct responses only. Children with a number of correct responses below 50% in any experimental sub-conditions were excluded from the analyses. Median RT of correct responses by sub-condition were adjusted (adjusRT) using the median RT obtained in Simple RT task. As accuracy data in both groups were at or near ceiling in all tasks (see Table 3), these were not included in the analyses.

AdjusRT data were included in different repeated measures ANCOVAs which evaluated, in both presentation formats (symbolic or non-symbolic), the effects of numerical processing (numerical size, numerical distance and size congruency). Shapiro–Wilk's normality test and Levene's variance homogeneity test indicated that the adjRTs data did not completely fit parametric assumptions of homogeneous variance and normal data distribution. Therefore, a logarithmic transformation was used in the adjRT analyses. Also, we tested (with T-tests) for differences between groups in Raven and Digit Span (forward and backward) scores. Digit Span scores were included because, as is described above, DD children seemss to have an atypical working memory development regarding TD children. In case of any significant differences arising between groups, these measures would be included as covariates in the variance analyses.

Table 3
AdjRT means (ms) and accuracy percentages by task and group

Group		Symbolic tasks		Non-symbolic tasks	
		Digit Comparison	Stroop	Collection Comparison	Stroop
TD	RT	453.3	470.39	492.41	884.1
(*N* = 33)		*(117.07)*	*(206)*	*(150.61)*	*(217.76)*
		95.33	96.78)	93.58	96.85
	Accuracy	*(3.65)*	*(3.97*	*(4.84)*	*(5.1)*
DD	RT	589.36**	639.21*	620.56*	1131.04*
(*N* = 32)		*(172.52)*	*(257.27)*	*(151.94)*	*(436.87)*
		94.66	96.29	94.77	95.24
	Accuracy	*(5.16)*	*(4.22)*	*(2.37)*	*(6.57)*

Notes: *SD* is shown in brackets.
Significant differences with the ajusRT for TD group: ** $p < .001$ and *$p < .01$

Results

Analysis of the Raven and Digit Span scores only showed significant differences between groups in the backward Digit Span, therefore this score was included as a covariate in all variance analyses.

Non- Symbolic Tasks

Analysis of Distance and Numerical Size Effects

A repeated measures ANOVA was run on median RTs with numerical size (small, large) and numerical distance (close, far) as within-subject factors; and group (DD, TD) as between-subjects factor. This analysis showed a numerical distance effect $F(1, 63) = 308.79$, $p < .001$ and a numerical size effect $F(1, 63) = 124.17$, $p < .001$. When the covariate was introduced, a group effect was found $F(1, 62) = 9.9594$, $p < .01$, the processing speed of the TD group was significantly lower than that of the DD group (see Table 3). An interaction between size and group was found $F(1, 62) = 7.2823$, $p < .01$. In the processing of small sizes, DD children showed a significant increase of 83.35 ms in their RT compared to TD children ($p < .001$), but there were no significant differences in the processing speed of large sizes.

Interaction between distance and group was not found. The groups only differed in processing speed: the TD group processed both numerical distances significantly faster than the DD group (close dist.: *TD* = 645.06 ms, *DD* = 781.87 ms, $p < .01$; far dist.: *TD* = 422.58 ms, *DD* = 530.30 ms, $p < .01$). Since the analysis of the size effect only showed significant differences in the processing of small sizes, the analysis of the distance effect was performed separately for each size (small and large). The analysis with small sizes showed a distance effect $F(1, 62) = 17.036$, $p < .001$ and a group effect $F(1, 62) = 15.602$, $p < .001$ and, although there was no interaction between distance and group, the groups were significantly different in their processing speed (close dist.: *TD* = 422.79 ms, *DD* = 583.64 ms, $p < .001$; far dist.: *TD* = 254.64 ms, *DD* = 379.3 ms, $p < .001$). In the analysis with large sizes only a distance effect was found $F(1, 62) = 10.322$, $p < .01$. Group effects or interactions between distance and group were not found. There was an interaction between size, distance and group $F(1, 62) = 6.1425$, $p < .05$. This interaction appeared as a product of the interaction between size and group described above. Data from this analysis are shown in Figure 1.

Analysis of Size Congruency Effect

A repeated measure ANOVA was run on median RTs with numerical size (small, large) and size congruency (congruent, incongruent) as within-subject factors; and group (*DD, TD*) as between-subjects factor. This analysis showed a numerical size effect $F(1, 65) = 6.5673$, $p < .05$, but no congruency effect. An interaction between congruency and numerical size $F(1, 65) = 18.968$, $p < .001$ was found. For congruent stimuli, a numerical size effect was not found, although the data show similarities with the classic effect (396.91 and 426.89 ms for small and large sizes respectively). However, for incongruent stimuli, an inverse numerical size effect appeared $F(1, 65) = 21.216$, $p < .001$ large sizes were processed significantly faster than small ones (391 279 ms and 559,267 ms, respectively). When the covariate was introduced, a group effect appeared $F(1, 64) = 8.3734$, $p < .01$. The processing speed of the TD group was significantly lower than the DD group (see Table 3). No interaction was found between size and group or between congruency and group. The differences are found only in the processing speed,

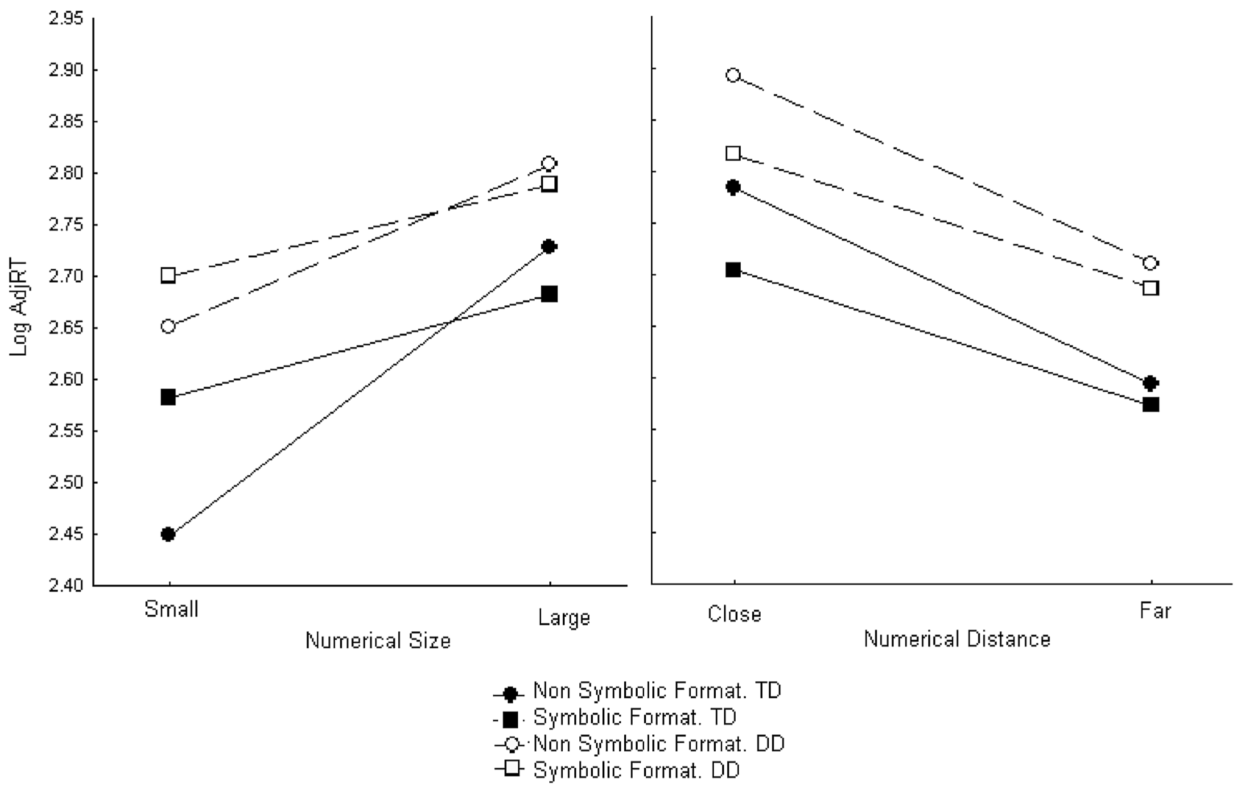

Figure 1. Distance and Numeric Size Effects for each presentation format (symbolic, non-symbolic)

where the DD group showed an increase in RT of 168.23 ms in processing congruent stimuli and of 126.47 ms when processing incongruent stimuli (p < .01 and p < .05 respectively), in comparison with the TD group. There was also no interaction between size, congruency and group. Data from this analysis are shown in Figure 2.

Symbolic Tasks

Analysis of Distance and Numerical Size Effects

A repeated measure ANOVA was run on median RTs with numerical size (small, large) and numerical distance (close, far) as within-subject factors; and group (*DD, DT*) as between-subjects factor. This analysis showed a numerical size effect $F(1, 63) = 113.51$, $p < .001$ and a numerical distance effect $F(1, 63) = 202.72$, $p < .001$. When the covariate was introduced, a group effect was found $F(1, 62) = 13.173$, $p < .001$ the processing speed of TD group was significantly lower than that of the DD group (see Table 3). Interaction between distance and group was not found. The groups only differed in processing speed. The DD group showed a significant RT increase of 167.7 ms in far distances and of 119.95 ms in close distances (p < .01 and p < .001, respectively), in comparison with the TD group. Similarly, interaction between size and group was not found. The groups differed only in processing speed. Regarding the TD group, the DD group showed a significant RT increase of 123.44 ms in small sizes and 155.33 ms in large sizes (p < .001 and p < .01 respectively). There was no interaction between size, distance and group. Data from this analysis are shown in Figure 1.

Analysis of Size Congruency Effect

A repeated measure ANOVA was run on median RTs with numerical size (small, large), numerical distance (close, far) and size congruency (congruent, incongruent) as within-subject factors; and group (DD, TD) as between-subjects factor. This analysis showed a congruency effect $F(1, 64) = 33.000$, $p < .001$ and numerical distance effect $F(1, 64) = 17.188$, $p < .001$. No numerical size effect was found. An interaction between distance and numerical size was found $F(1, 64) = 10.699$, $p < .01$, but not between congruency and numerical size, or between congruency and numerical distance. However, it is noteworthy that even if in the incongruent condition there was no numerical distance effect, in the congruent condition this effect appeared inversely ($F(1, 64) = 12.096$, $p < .001$) close distances were processed faster. This pattern is maintained for both groups of children. When the covariate was introduced, a group effect appeared: $F(1, 63) = 7.4090$, $p < .01$. The processing

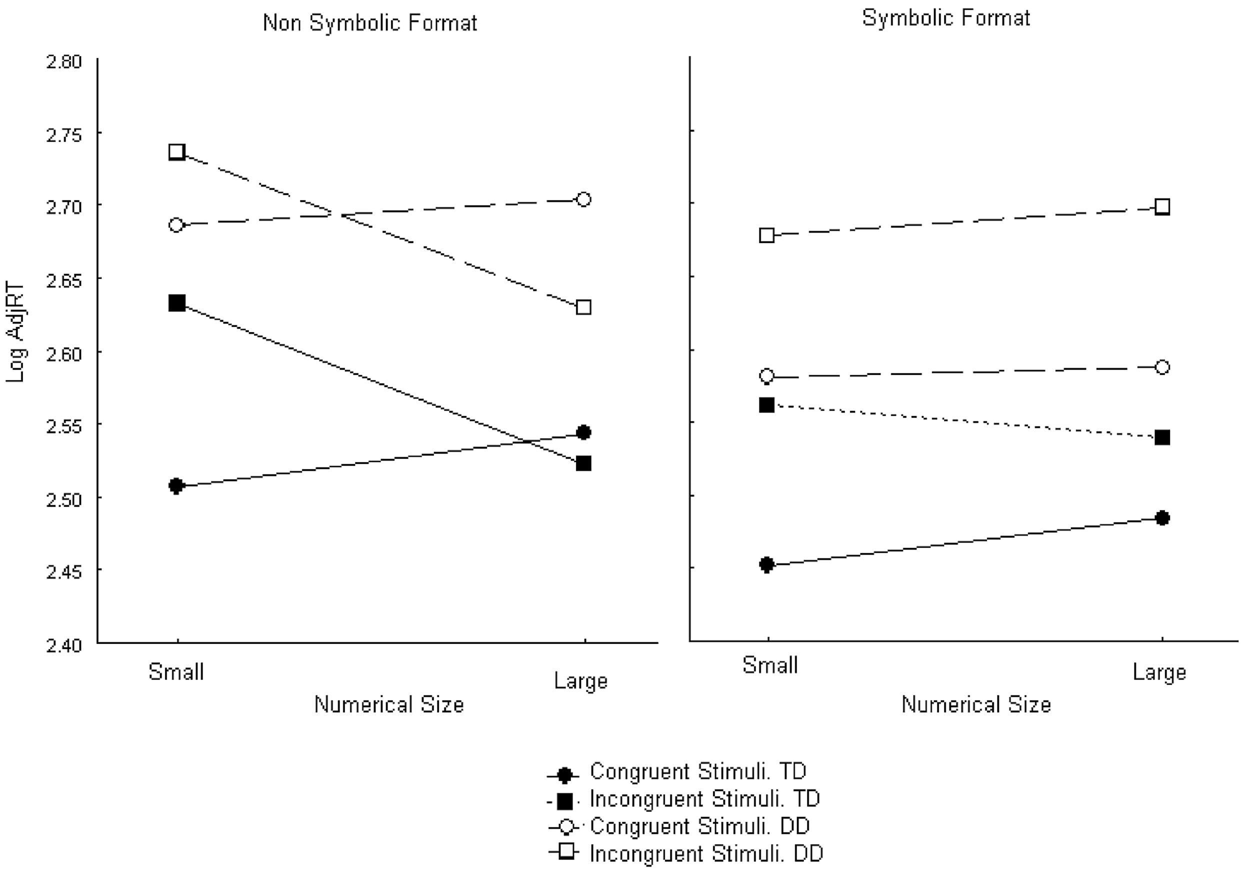

Figure 2. Size Congruency Effect for each presentation format (symbolic, non-symbolic).

speed of the TD group was significantly lower than that of the DD group (see Table 3). Interaction between congruency and group was not found. The differences appear only in processing speed, where the DD group was significantly slower than the TD group for each condition (congruent, TD = 331.68 ms, DD = 435.06 ms, $p < .05$; incongruent, TD = 400.87 ms, DD = 533.18 ms, $p < .01$) (see Figure 2). Interactions between numerical size and group or between numerical size, distance and group were not found.

Analysis of Presentation Format Effect in numerical comparison tasks (digit comparison vs. collection comparison)

The above data show the performance of DD and TD children for each format separately. In this section, taking into consideration the presentation format (symbolic, non-symbolic), the results between groups (DD, TD) are contrasted. As others effects have already been analyzed, only the results corresponding to presentation format will be described here. A repeated measure ANOVA was run on median RTs with presentation format (non-symbolic, symbolic), numerical size (small, large) and numerical distance (close, far) as within-subject factors; and group (DD, TD) as between-subjects factor. This analysis showed no format effect, but an interaction between format and numerical size was found $F(1, 64) = 39{,}403$, $p < .001$. When analyzing large sizes, we found that they were processed faster in the symbolic format ($p < .01$). On the contrary, small sizes were processed significantly faster when they were presented in the non-symbolic format ($p < .001$). This performance pattern may be due to the instant processing that characterises the manipulation of numbers in the subitizing range. An interaction between format and numerical distance was found $F(1, 63) = 41{,}620$, $p < .001$. For close distances, a presentation format effect was not found, while for far distances, non-symbolic stimuli were processed faster ($p < .05$). When the covariate was introduced, a group effect appeared F (1, 62) = 17,955, $p < .001$. An interaction between format, numerical size and group was found, $F(1, 62) = 5{,}7610$, $p < .05$. In small sizes, the TD group processed non-symbolic stimuli significantly faster, ($F(1, 62) = 9{,}8393$, $p < .01$), and in large sizes, the symbolic stimuli ($F(1, 62) = 11{,}6069$, $p < .01$). On the contrary, the DD group processed both symbolic and non-symbolic stimuli in a similar way. No interactions between format, numerical distance and group or between format, size, numerical distance and group were found (see Figure 1).

Discussion

In this study, two hypotheses about the possible cognitive mechanisms underlying DD were contrasted. The hypothesis of a deficit in numerical representation proposes two variants of possible deficits: one deficit is in number sense, which refers to difficulties with the handling and representation of approximate quantities; and the other deficit, in the number module, responsible for the representation and manipulation of exact numerosities. The other hypothesis assumes that the dysfunction is not in numerical representation *per se*, but rather in the connection between numerical symbols and the analogous quantities represent by them. The low difficulty level of the tasks was selected to assess whether DD children would experience difficulties, even for the most basic requirements of these tasks. The high accuracy levels obtained by these children lead to the assumption that numerical representation may be intact and that it is mainly the processing component that is deficient.

In the non-symbolic comparison tasks, both groups showed similar achievement patterns in numerical distance and size congruency effects, and similar processing speed except for small sizes. These findings support previous evidence that suggests that DD children are slower to compare numerosities in the subitizing range (Koontz & Berch, 1996) and that difficulties in this processing range can be shared with a normal development of counting and magnitude comparisons (Bruandet, Molko, Cohen, & Dehaene, 2004). In symbolic comparison tasks, children with DD showed similar distance, size and size congruency effects, but their response latencies were much higher than those of the TD group. Similar results have been found in previous studies with similar or younger children (Bachot, Gevers, Fias, & Roeyers, 2005; Landerl et al., 2009; Landerl & Kölle, 2009; Rousselle & Nöel, 2007).

As noted in section "Non-symbolic Tasks", Rousselle and Nöel's (2007) design did not include collections with numerosities between 1 and 4. The authors, based on previous evidence (Simon, 1997; Trick & Pylyshyn, 1994), argue that numerosities in subitizing range are apprehended through quantification processes different from counting and approximate estimation in larger numerosities. Therefore, these processes may not reflect the typical characteristics of the comparison process. In accordance with this, it has been described in the proposals of object file system (Carey, 2001; 2004; Wynn, 1990; 1992) that, when comparing small collections, numerosities are bootstrapped by assigning an index to each object, which remains in memory when the collection is not longer available. Numerosity discrimination would result from the observation of a disparity in the one-to-one correspondence between the mental index stored in memory and objects in a new set. This process does not reflect a numerosity representation *per se*, but rather a more general cognitive mechanism associated with selective attention and working memory (with a limit of amount, usually up to four elements) by which the sets are represented as "objects" with different properties, but not as sets with a cardinal value (Feigenson et al., 2002; Rousselle, Palmers, & Nöel, 2004; Simon, 1997; Leslie, Xu, Tremoulet, & Scholl, 1998; Xu & Spelke, 2000). Then, it is considered that, as a product of the visual-spatial nature of non-symbolic tasks, a plausible explanation for discalculic children results in the processing of small sizes is that their subitizing range difficulties may reflect attentional and working memory deficits rather than numerical representation deficits.

On the other hand, the deficit in numerical representation hypothesis (whether the deficit is in number sense or in numerical module) suggests that DD children should not show a non-intentional processing of numerical size represented through symbols, as result of a deficit in the numerical concepts representation. However, the high accuracy of their responses and the emergence of a congruency effect similar to the TD group show that they do. Another sign of numerical processing that was found, is that the achievement of DD children has been influenced by the distance and numerical size of the collection pairs (which is expressed in distance and numerical size effects similar to those for the TD group). These data, consistent with recent evidence found by Landerl et al. (2009), Landerl and Kölle (2009) and, De Smedt and Gilmore (2011), indicate that the numerical representation of DD children may be intact and that the problem is in the accessing and processing of these representations, rather than in the representation *per se*. This is in line with the proposal of the access deficit hypothesis.

Other data that suggest that the deficit in DD could be in processing and not in numeric representation arise from studies with DD children older than 10 years (Kucian et al., 2006; Mussolin, Mejias, & Nöel, 2010; Soltész, Szücs, Dékány, Markus, & Csépe, 2007). In these studies, no differences were found in the processing speed in symbolic tasks between these children and children without difficulties. Studies on the typical development of numeracy skills show that, with increasing age and education, long-term memory associations between compared pairs of digits and the correct response are developed. This leads to an automatization of the size comparison process, with a consequent decrease in task execution time (Castro et al., 2011; Logan, 1988; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Tzelgov, Meyer, & Henik, 1992). It appears that the development of numeracy skills could follow, in children with DD, a similar pattern to that of typical development. Therefore, the achievement of DD children may be improved and may eventually reach a similar skill level than that of children without arithmetic difficulties. However, more empirical evidence is required to corroborate this hypothesis, especially through longitudinal studies that show how size processing develops in DD children, and how this development differs from typical development.

Conclusions

The DD children of this study show a deficit in the processing of analogous magnitudes in the subitizing range that appears to be linked to attentional and / or working memory difficulties, while the numerical representation seems to be intact. This is expressed in similar numerical distance and size congruency effects to those exhibited by children with typical development. In the symbolic tasks, DD children processed numerosities significantly slower than the controls.

These data fit the access deficit hypothesis, which states that the core deficit in DD does not lie in a deficient numerical representation but rather in a deficit in the connection between symbolic and analogous representations. Subtle deficiencies in the integration of the numerical representation core systems (analogous and verbal) may prevent DD children from developing an accurate understanding of how numerical symbols (e.g., Arabic digits) represent analogous magnitudes (non-symbolic). It is assumed that having a precise semantic representation of numbers that is not fully developed or automatically available, may have a strong negative impact on, if not all, at least most arithmetic activities. These results provide new evidence on the need to implement educational systems and interventions aimed at strengthening the connection between numerical symbols and the concepts that it represent.

The precise deficit that causes, in DD children, the appearance of the "disconnection" between numerical symbols and analogous magnitudes remains to be clarified. It may be an interface deficit between the symbolic and analogous systems or a deficit in the verbal processing system (which is responsible for the symbolic representations) *per se*. Alternatively, the existence of weak connections between symbols and their underlying quantities could make the learning of symbolic representations harder for children during development. These ideas suggest the need for research with tasks that assess the interface between representational systems of DD children.

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