# Number Processing and Heterogeneity of Developmental Dyscalculia: Subtypes With Different Cognitive Profiles and Deficits

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# Number Processing and Heterogeneity of Developmental Dyscalculia: Subtypes With Different Cognitive Profiles and Deficits

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## Abstract

This study investigated if developmental dyscalculia (DD) in children with different profiles of mathematical deficits has the same or different cognitive origins. The defective approximate number system hypothesis and the access deficit hypothesis were tested using two different groups of children with DD (11–13 years old): a group with arithmetic fact dyscalculia (AFD) and a group with general dyscalculia (GD). Several different aspects of number magnitude processing were assessed in these two groups and compared with age-matched typically achieving children. The GD group displayed weaknesses with both symbolic and nonsymbolic number processing, whereas the AFD group displayed problems only with symbolic number processing. These findings provide evidence that the origins of DD in children with different profiles of mathematical problems diverge. Children with GD have impairment in the innate approximate number system, whereas children with AFD suffer from an access deficit. These findings have implications for researchers' selection procedures when studying dyscalculia, and also for practitioners in the educational setting.

## Keywords

developmental dyscalculia, symbolic number processing, nonsymbolic number processing, calculation, arithmetic fact retrieval

Acquisition of numerical competency is imperative for individuals in contemporary society, both for quality of life and economic well-being, and low numeracy is a substantial cost to nations (Butterworth, Varma, & Laurillard, 2011). The newly released fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (American Psychiatric Association, 2013) states that 5% to 15% of school-aged children may suffer from a specific learning disorder that may hamper the acquisition of numerical competency. Developmental dyscalculia (DD) is one of those specific learning disorders, and it is characterized by impairments in learning and remembering arithmetic facts and in executing calculation procedures (Butterworth, 2005).

Because of the high prevalence rate, which is estimated to be about 3% to 6% in the general population (Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Rubinsten & Henik, 2009; Shalev, 2007), it is of great importance to investigate the origin of DD. Although researchers generally agree that DD is partly caused by biological factors, research has generated mixed results concerning the particular neurocognitive profile and origin of DD. A review of prior studies suggests that different age groups, cutoff criteria, and mathematical screening measures might account for this state of affairs. More specifically, some studies have used multifaceted test batteries as screening measures, tapping aspects such as basic number knowledge, simple one-digit arithmetic, and multidigit calculation (e.g., Piazza et al., 2010; Rousselle & Noël, 2007), whereas other studies have focused exclusively on arithmetic fact retrieval (e.g., Landerl, Bevan, & Butterworth, 2004; Mussolin, Mejias, & Noël, 2010). Furthermore, the cutoff criteria used in studies conducted during the past 10 years have ranged from the conservative criteria of 2.28th percentile used by Landerl et al. (2004) to the more common criteria at or below the 15th percentile to classify children as having DD (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009; Rousselle & Noël, 2007). Previous research has also displayed a large disparity in age range investigated across studies, ranging from 14 years in Mazzocco, Feigenson, and Halberda (2011) to 6 to 7 years in De Smedt and Gilmore (2011), and 9 to 11 years is the most common age range (e.g., Mussolin et al., 2010; Piazza et al., 2010).

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The variability of selection procedures is a critical issue because it might result in diverse samples of children with DD across studies, which probably explains the inconsistent findings. Diverse samples are, however, consistent with the increasingly recognized position that DD is a heterogeneous condition, where children with DD display different profiles of mathematical deficits (De Visscher & Noël, 2013; Geary, Hoard, & Hamson, 1999; Jordan & Montani, 1997; Temple, 1991; Von Aster & Shalev, 2007). Number processing is represented and reliant on cortical activity in several brain areas connected through complex distributed networks; it is therefore likely that there are numerous vulnerable sites in the processing chain that are susceptible to deviations, which ultimately may impair number processing (Rubinsten & Henik, 2009). For instance, the intraparietal sulcus (IPS) has been found to be involved during nonsymbolic processing, whereas symbolic processing involves the IPS, angular gyrus (Price & Ansari, 2011), and inferior frontal gyrus (Nieder, 2009). Moreover, these areas are involved not only during number processing but also in other mental functions, such as attention (Henik, Rubinsten, & Ashkenazi, 2011), and are connected through white matter tracts that incidentally also have been found to be implicated in DD (Rykhlevskaia, Uddin, Kondos, & Menon, 2009).

Although DD can be divided into different subtypes with respect to comorbidities, such as attention-deficit/hyperactivity disorder (ADHD) and reading disabilities, it is also likely that "pure" DD itself is subject to heterogeneous subtypes. A recent case study of a woman with a severe arithmetic fact retrieval deficit simultaneously showed intact nonsymbolic number processing skills usually associated with DD. The authors suggested that *arithmetic fact dyscalculia* (AFD) might be one subtype of pure DD (De Visscher & Noël, 2013).

Based on this position that DD might arise from multiple brain dysfunctions and cognitive deficits, and that the cardinal deficits of DD are difficulties with arithmetic fact retrieval and execution of calculation procedures (Andersson, 2010; Jordan & Hanich, 2003; Jordan, Hanich, & Kaplan, 2003; Jordan, Kaplan, & Hanich, 2002; Russell & Ginsburg, 1984), the aim of this study was to investigate if DD in children with different profiles of mathematical deficits have the same or different cognitive origins. This was accomplished by examining children with severe arithmetic fact retrieval deficits but normal calculation ability, corresponding to the suggested subtype of DD by De Visscher and Noël (2013), and children with severe deficits in arithmetic fact retrieval *and* calculation ability, corresponding to the conventional notion of DD. These two subgroups were compared with children consisting of age-matched typical achievers regarding math performance.

Although the underlying cause of DD remains unresolved, different hypotheses have been proposed, and two of them were tested and contrasted in the present study.

### *The Defective ANS Hypothesis*

Extensive and fruitful research carried out during the past 25 years demonstrates that humans have an innate preverbal ability to represent and manipulate quantities that constitutes the foundation for the acquisition of the symbolic number system used for learning formal arithmetic (Dehaene, 2011; Gallistel & Gelman, 1992; Gelman & Butterworth, 2005; Piazza, 2010; Wynn, 1992, 1995; Xu & Spelke, 2000). According to some researchers, DD in children is caused by impairment in this innate number ability (Dehaene, 2011; Gallistel & Gelman, 1992; Gelman & Butterworth, 2005; Piazza, 2010; Wynn, 1992, 1995; Xu & Spelke, 2000). More specifically, they propose that the deficit is located in the approximate number system (ANS) responsible for representing large and approximate numbers via a logarithmic analogue mental number line (Dehaene, 2011; de Hevia, Vallar, & Girelli, 2006; Feigenson, Dehaene, & Spelke, 2004; Le Corre & Carey, 2007). In this system, numerosities are mapped onto the number line, and the increasing magnitudes are represented in ascending order, from left to right, whereas each number is associated with a spatial location (de Hevia et al., 2006; Previtali, de Hevia, & Girelli, 2010). A main feature of the ANS is its imprecision, which is due to its logarithmic nature, that is, larger numbers are closer together than smaller numbers (Bugden & Ansari, 2011; Dehaene, 1992; de Hevia et al., 2006; Feigenson et al., 2004). However, it is believed that with increasing experience with the symbolic system children learn to compensate for the logarithmic nature of the symbolic ANS or that the ANS is sharpened through the acquisition of the exact symbolic number system (Feigenson et al., 2004; Halberda & Feigenson, 2008; Mundy & Gilmore, 2009).

### *The Access Deficit Hypothesis*

Rousselle and Noël (2007) have proposed another domain specific account of DD in children, which they call the "access deficit hypothesis." This hypothesis states that DD in children is related not to problems with processing of numerosities, but rather with accessing magnitude information from symbols (i.e., numerals). Thus, the main causal element in DD is attributable to the connection between symbolic numbers and innate magnitude representations (Rousselle & Noël, 2007; also see Wilson & Dehaene, 2007). It follows from this hypothesis that children with DD should display problems only with symbolic (numerals) number magnitude processing tasks but perform within normal range on nonsymbolic tasks because only the former type of task requires access to the underlying magnitude representations of Arabic numerals (Rousselle & Noël, 2007; also see Wilson & Dehaene, 2007). Considering the innate ANS, in contrast, impairment in this system should affect all number magnitude-processing tasks (nonsymbolic and symbolic) and influence number magnitude processing effects (e.g., distance and problem size effects) because they all reflect the logarithmic and analogue nature of the ANS (Piazza, 2010; Rousselle & Noël, 2007; Wilson & Dehaene, 2007).

## *Research in Relation to the Defective ANS Hypothesis and the Access Deficit Hypothesis*

There is ample evidence showing that children with DD perform poorly when they have to select the numerically larger of two Arabic numerals, which requires activation of the magnitude representations associated to the two numerals (Iuculano, Tang, Hall, & Butterworth, 2008; Landerl et al., 2004; Landerl et al., 2009; Landerl & Kölle, 2009; Rousselle & Noël, 2007). There are a couple of ways of interpreting this; one could regard these results as an indication that children with DD perform poorly because of a connection deficit between the symbolic and nonsymbolic systems, or one could attribute it to a defective ANS.

Other interesting aspects of the numerical comparison task are the manipulation of the numerical distance between the numerals (distance effect) and the magnitude of the pairs to be compared (problem size effect). The distance effect refers to the fact that the choice of the larger of two numerals is faster when the numerical distance is large compared to small (Moyer & Landauer, 1967). The problem size effect connotes that the selection of the larger of two numerals is performed faster when the numerals are small (3 vs. 4) than when they are large (9 vs. 8). These two effects are considered to demonstrate that the magnitude representations associated with numerals and counting words are represented mentally as approximate analogue magnitudes (e.g., mental number line). Since the distance and problem size effects are reduced with ontogenetic development in typical children (Holloway & Ansari, 2008, 2009; Landerl & Kölle, 2009), it has been considered a fruitful approach to examine these effects to identify children with DD, which might then be interpreted as a deficiency in the ANS (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Landerl et al., 2009).

Results from studies investigating the aforementioned effects in children with DD have been mixed. For example, Landerl and colleagues (Landerl et al., 2009; Landerl & Kölle, 2009) and Ashkenazi, Mark-Zigdon, and Henik (2009) found that children with DD display the distance effect on one-digit comparison tasks to the same extent as the controls. In a more recent study, by Mussolin et al. (2010), the DD children demonstrated a larger distance effect on both symbolic as well as nonsymbolic magnitude comparison tasks. Furthermore, Ashkenazi et al. demonstrated larger distance effect as well as a larger problem size effect compared with controls on a two-digit numerical comparison task.

These findings are congruent with the defective ANS hypothesis because the results suggest that the ANS in children with DD are less precise and more logarithmic, resulting in increased difficulties with distinguishing and comparing numerals and numerosities (Ashkenazi et al., 2009; Geary et al., 2008; Landerl et al., 2009; Mussolin et al., 2010; Rousselle & Noël, 2007). Strong evidence for a deficit in the ANS has been provided by a number of studies showing that children with DD perform poorly on nonsymbolic number discrimination or estimation (Landerl et al., 2009; Mazzocco et al., 2011; Mejias, Mussolin, Rousselle, Grégoire, & Noël, 2012; Mussolin et al., 2010; Piazza et al., 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Piazza et al. (2010) and Mazzocco et al. (2011) estimated the acuity, that is, the precision and discriminability of the ANS by computing Weber fractions (W) for each child. Piazza et al. concluded that the DD children displayed a defective ANS, as their mean W value of .34 was considerably higher than their age-matched controls' W value of .25 and was comparable to that of the 5-year-old children participating in the study. Mazzocco et al. (2011) replicated Piazza et al.'s findings and observed that ninth graders with DD displayed impairment in the acuity of the ANS as indicated by their high W value. It should be noted, however, that some studies have found that children with DD perform poorly only on symbolic number discrimination, not on nonsymbolic number discrimination, which is in line with the access deficit hypothesis (De Smedt & Gilmore, 2011; Iuculano et al., 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007).

Additional support for a domain-specific number deficit in DD is provided by studies using the number line estimation task (see Siegler & Opfer, 2003). These studies show that children with DD have problems developing a linear mental number line representation of good quality (Geary et al., 2007; Geary et al., 2008; Landerl et al., 2009). However, as this task assesses the ANS, the symbolic number system, and the connection between them (LeFevre et al., 2010; Piazza, 2010; Siegler & Opfer, 2003), these findings provide support for both the defective ANS hypothesis and the access deficit hypothesis.

To summarize, available research provides robust empirical support for a number processing deficit in children with DD. However, the findings are inconclusive with respect to the hypotheses outlined above, and especially in relation to children with different profiles of mathematical deficits. So far only De Visscher and Noël (2013) have tested hypotheses regarding the origin of DD in children with specific profiles of mathematical deficits. They found an interference-related deficit in a case of pure arithmetic fact retrieval dyscalculia, but no support for the defective ANS hypothesis. In their case study, De Visscher and Noël (2013) argue that one possible cause of AFD might be attributed to a heightened sensitivity to interference, which would hamper the ability to memorize arithmetic facts in the first place. One tentative hypothesis of the neurological correlate of AFD is that individuals with this profile have impaired functional connectivity between the hippocampus and angular gyrus, which is believed to be responsible for memory formation of arithmetic facts (De Visscher & Noël, 2013). Ansari (2008) also suggested that the angylar gyrus subserves automatic mapping between mathematical symbols and their semantic referents, which invites the hypothesis that children with AFD also might have problems in accessing the nonsymbolic magnitude representations, even if the representations themselves are intact (i.e., the access deficit hypothesis).

Thus, further research is warranted to deepen our understanding of the underlying causes of DD in children with distinct profiles of mathematical deficits.

### The Present Study

The aim of present study was to investigate if DD in children with different profiles of mathematical deficits has the same or different origins. More specifically, the defective ANS hypothesis and the access deficit hypothesis were tested using one group of children with AFD and one group with general dyscalculia (GD).

The participating children were between 10 and 13 years of age. The rationale behind choosing children in this age range was to ensure that mathematical deficits of children were not due to a developmental delay and that they had adequate experience with numerals and arithmetic. Moreover, since most prior studies have focused on children aged 9 to 10, it would be interesting to investigate whether older children with DD display similar cognitive profile as younger children. The following hypotheses were predicted:

1. If the defective ANS hypothesis is correct, children with GD and/or AFD should display problems with estimation tasks, such as dot magnitude discrimination, in conjunction with symbolic number tasks, because the ANS is a prerequisite and foundation for the development of the symbolic system (cf. Wilson & Dehaene, 2007), and therefore they should show a greater distance effect as well as the problem size effect.
2. According to the access deficit hypothesis, children with GD and/or AFD should display intact abilities on nonsymbolic tasks but have difficulties with symbolic number tasks.

## Method

### Participants

A total of 77 children attending 12 different schools participated in the study. Of these children, 11 children were in their fourth year, 41 were in their fifth year, and 25 were in their sixth year of schooling. The total sample had a mean age of 11 years, 9 months (range = 10 years, 3 months to 13 years, 0 months). All children had Swedish as their primary language, had normal or corrected-to-normal visual acuity, and had no hearing loss. The present study employed a similar approach to classify children as having DD as used by Andersson (2010). The first selection criterion was that the child received special education instruction in mathematics at the time of the study. To receive special instructions, the child must have displayed poor achievement and poor skill development during a period of time. Each teacher responsible for the special instructions was also asked to identify and exclude children with diagnosed ADHD and children whom he or she believed might have undiagnosed ADHD or mathematical deficits due to other neurological disturbances. To identify children with AFD or GD, a paper-and-pencil multidigit arithmetic calculation task and computer-administered arithmetic fact retrieval task were used (see description below). The second selection criterion used to identify children with GD was that the child's scores on the arithmetic fact retrieval task (GD: 1.00 ± 1.50 percentile) and the calculation tasks (GD: 1.00 ± 0.50 percentile) were at or below the 5th percentile of an age-matched norm group (Träff, 2012). To be classified as AFD, the child's scores on the arithmetic fact retrieval task (AFD: 1.00 ± 1.50 percentile) had to be at or below the 5th percentile of an age-matched norm group and the scores on the calculation tasks (AFD: 21.50 ± 3.50 percentile) at or above the 15th percentile. The typical achiever (TA) children were randomly selected from the same classrooms as the AFD and the GD children. The criteria were that the child did not receive any special instruction and that the child's scores on the arithmetic fact retrieval task (TA: 50.00 ± 17.00 percentile) and the calculation tasks (TA: 71.00 ± 23.50 percentile) were at or above the 15th percentile. In all, 16 children fit the criteria for inclusion in the AFD group, 34 children were included in the GD group, and 27 children were included in the TA group.

In addition to the arithmetic tasks, the following tasks were administered to tap general cognitive abilities and reading skill: reading comprehension task, verbal and visual working memory, *Raven's Standard Progressive Matrices Test* (Sets B, C, and D; Raven, 1976), color naming, and color Stroop task (inhibition control). More detailed descriptions of these tasks are presented below. Background information and results on the tasks are displayed for each ability group in Table 1.

A one-way analysis of variance (ANOVA) and Tukey–Kramer post hoc test displayed that the GD group (25.00 ± 22.19 percentile) but not the AFD group (54.50 ± 26.10 percentile) displayed lower raw scores on Raven's test, $F(2, 74) = 13.03$, $p < .001$, compared to the TA group (75.00 ± 26.66 percentile). Due to this, ANCOVAs with Raven's test

**Table 1.** Descriptive Data (Raw Scores) for Children in the AFD Group, the GD Group, and the TA Group.

| | AFD | | GD | | TA | |
|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| *n* (number of boys) | 16 (4) | | 34 (19) | | 27 (11) | |
| Mean age (in months) | 142 | 6.16 | 141 | 7.51 | 142 | 9.76 |
| Reading task | 15.63 | 6.41 | 12.53 | 4.81 | 22.19 | 4.00 |
| Verbal working memory | 3.69 | 0.77 | 3.25 | 0.76 | 3.91 | 1.00 |
| Visuospatial working memory | 3.38 | 1.20 | 3.16 | 1.00 | 3.83 | 1.17 |
| Inhibition control | 20.78 | 14.40 | 27.18 | 13.85 | 15.98 | 6.30 |
| Color naming | 54.56 | 14.67 | 55.47 | 13.87 | 41.74 | 7.13 |

*Note.* AFD = arithmetic fact dyscalculia; GD = general dyscalculia; TA = typical achievers.

as a covariate were used to compare the three groups on measures of reading, verbal working memory, visuospatial working memory, inhibition control, color naming, and reading. These analyses displayed that both the AFD and GD groups displayed poorer performance on reading, $F(2, 73) = 22.26$, $p < .001$, and color naming, $F(2, 73) = 8.06$, $p = .001$, compared with the TA group. Furthermore, the GD group also performed slower than the TA group on the inhibition control task, $F(2, 73) = 5.00$, $p = .009$. The AFD and GD groups' performances on the verbal and visuospatial working memory tasks were equal to that of the TA group. However, including the reading task as an additional covariate eliminated the poorer performance of the GD group on the inhibition control measure and the slower color naming performance of the GD and AFD group.

## Screening Tests

*Raven's Standard Progressive Matrices Test.* This is a well-known and frequently used test of nonverbal logical reasoning and consists of a series of visual pattern designs with a piece missing (Raven, 1976). The task is to select the correct piece to complete the designs from a number of options (six to eight) displayed beneath the design. The test includes five sets of designs (A, B, C, D, E) with 12 items per set. Only Sets B, C, and D were used in this study. Each child received a test booklet, and after two practice items had been performed, the children individually completed the 36 items at their own pace. The Cronbach's alpha calculated on the three sets was .87.

*Reading task.* The test consisted of 12 short stories to be read, followed by a multiple-choice questionnaire related to each story assessing the children's general reading comprehension level (Malmquist, 1977). The test contained 33 questions, and all questions were to be answered within a time limit of 4 min. The total number of correct answers was the dependent measure. The split-half reliability after Spearman–Brown correction for this task is .97 (Malmquist, 1977).

*Arithmetic fact retrieval and arithmetic calculation.* The arithmetic fact retrieval task was administered via a computer and consisted of 12 addition problems (e.g., 9 + 5; 4 + 6), 12 subtraction problems (8 – 4; 6 – 2), and 12 multiplication problems (4 × 5; 7 × 3). The three arithmetic operations were administered in separate blocks. One problem at a time was presented horizontally on the computer screen. When the child announced that he or she was ready, the experimenter pressed the mouse button and a problem was displayed on the computer screen until the child had responded. A timer started at the onset of the problem and was stopped when the experimenter pressed the mouse button after the child had given an oral response to the problem. The child was instructed to provide an answer immediately by remembering what the answer was and was encouraged to guess if he or she failed to do so. To ensure that the task tapped fact retrieval rather than calculation, only the number of correctly solved problems with response times within 3,000 ms was used as the dependent measure (cf. Russell & Ginsburg, 1984). The Cronbach's alpha calculated on the current sample using the three blocks was .94.

Arithmetic calculation ability was tapped using three paper-and-pencil tasks designed so that the test items became successively more difficult. All three tasks were administered in groups of four children, the number of correctly solved problems was the dependent measure, and the combined maximum score was 32. The same test procedure (i.e., instructions, paper and pencil, scoring procedure) was used in all three subtasks. In the first calculation subtask, the child was asked to solve five addition problems and five subtraction problems (e.g., 568 + 421, 658 – 437, 4,203 + 5,825) in 8 min. The problems were presented horizontally, and the child responded in writing. All problems except two involved regrouping (i.e., carrying or borrowing). The children could solve the problems in any way according to their own preference, but only with paper and pencil at their disposal. The task was administered in groups of four children. Subtask 2 consisted of 12 arithmetic equations presented horizontally (e.g., 61 + ___ = 73; ___ – 500 = 50). The task was to fill in the right number so the equation was correct. The child had 7 min to solve the equations. In the third subtask, the child was presented with an answer and two to four numbers that had to be combined with one to three arithmetic operators (addition, subtraction, multiplication) to obtain the predetermined answer. If the answer was 30 and the three numbers were 10, 50, 90, a correct combination would be 90 – 10 – 50. The child had 5 min to solve 10 problems (e.g., 27, 113 = 140; 25, 19, 11 = 5). The Cronbach's alpha calculated on the three subtasks was .89.

The arithmetic tasks (fact retrieval, calculation) have been standardized and normed on 110 fourth graders, 110 fifth graders, and 110 sixth graders sampled from 20 urban schools. The mean socioeconomic status of the samples was primarily middle class but varied from lower middle class to upper middle class. The data were collected in the spring semester from January to May. The arithmetic calculation tasks were administered in groups of four children, whereas the fact retrieval task was administered individually. Cronbach's alpha coefficients for the three calculations tasks calculated on children aged between 9 and 11 years ranged from .74 to 82, whereas the Cronbach's alpha coefficient for the fact retrieval task calculated on all 36 trials was .87.

*Listening span task.* This task measures the participants' verbal working memory capacity and was administered to control for the influence of working memory capacity on arithmetic abilities. The participant was orally presented with sequences of three-word sentences, and the initial task was to determine whether the sentence makes semantic and syntactic sense or not. Thus, the participant was to respond yes if the sentence made sense (e.g., "The rabbit was fast") or "no" if the presented sentence was absurd (e.g., "The frog played the piano"). The participant was also told, prior to the first trial, to try to remember the first word in each sentence regardless of whether the sentence was absurd or not. After orally answering "yes" or "no," the next sentence was presented. The first span size level was 2, and therefore the number of sentences read to the participants was also 2, after which the participant had to recall in correct serial order the target words. The next span size was 3, and the number of sentences and target words were of equal quantity as the span size, after which another response phase followed. The span size ranged from 3 to 7, and there were two trials for each span size. The longest correctly recalled list was used as the dependent measure (maximum score = 7.5), and the participant had to respond correctly whether the sentences were correct or not. Half of the sentences were normal and half of the sentences were absurd. Each sentence was read to the participant, word by word, at a rate of approximately one word per 0.5 s. The Spearman–Brown reliability calculated between the A and B trials was $r_{sh} = .90$.

*Visual matrix task.* This computerized visuospatial working memory task was administered to control for the influence of working memory capacity on arithmetic abilities, and consists of a matrix of squares, where each square was sized 2.5 × 2.5 cm. The number of squares in each matrix varied and increased as to make it more difficult for each successful trial. Initially, the matrix consisted of 3 × 3 squares, where some squares contained two black dots, and the participant was at first to estimate whether these dots were of equal size or not and subsequently press asterisk key if they were equal or the A key if they were not. The participant had 3 s to respond, after which two additional dots appeared in another square while the former two dots were still visible. Once again the participant had to decide whether these two dots were of equal size and respond accordingly within 3 s. In addition to making these judgments, the participant had to remember in which squares the dots had been presented because the matrix disappeared after a given sequence of dots had been presented, and the participant had to mark on piece of paper containing an identical matrix as had been previously shown in which squares the participant believed the dots had been shown. The initial matrix had 3 × 3 squares, as mentioned above, in which two squares contained black dots, resulting in a trial of span size 2. The following matrix had 3 × 4 squares in which three squares black dots appeared, giving a span size of 3. The third, fourth, fifth, and sixth levels had 16, 20, 25, and 30 squares, respectively, in which the third level had 4 dots, the fourth level had 5 dots, the fifth level had 6 dots, and the sixth level had 7 dots appearing within the matrix. Thus, this task measured the span size between 2 and 7 items. For each span size, there were two matrices presented to the participants. The most complex matrix correctly recalled (i.e., locations of dots) was used as the dependent measure. However, the participants also had to respond correctly to each and every process question (i.e., the size decision) to receive points for the matrix. The maximum score on this task was 7.5. The Spearman–Brown reliability coefficient was $r_{sh} = .74$.

*Color naming and color Stroop task.* Color naming is a type of rapid automatized naming (RAN) task (Denckla & Rudel, 1976) and is used as a control task because it involves behavioral responses involved in other numerical tasks, such as digit naming, where the RAN task is used to control for lexical speed of access to color names. Performance on this task is also used as a measure of general speed and used in ANCOVAs to control for cognitive speed in number processing tasks where speed is of the essence. This task consisted of two conditions, a color naming condition and a color Stroop incongruent condition. The first condition, color naming, was administered on two separate sheets of A4 paper, where strings of "XXX" (Arial 22-point font) were printed in different colors, red, green, blue, black, or yellow, and in two separate columns for a total of 30 XXX strings. The participant was instructed to name the color in which the strings were printed as fast as possible without making any errors. A stopwatch was used to measure the total response time used as the performance measure. The combined response times for the two sheets of paper were used as a measure of speed of access to semantic information in long-term memory (Temple & Sherwood, 2002). The Spearman–Brown reliability calculated between the first trial and second trial was $r_{sh}$ = .90.

In the color Stroop incongruent condition, the stimuli consisted of 30 color words (red, green, blue, black, and yellow); the words named a color incongruent with the ink colors in which they were printed (e.g., the word "RED" in green ink). The task was to name aloud as quickly as possible the ink color in which each word was printed while ignoring the word's identity. A measure of inhibition control was obtained by subtracting the mean response time for the two color naming trials from the total response time for the incongruent condition (e.g., incongruent – naming of color XXX). The correlation between the incongruent condition and the color naming condition was $r$ = .77.

## *Experimental Number Processing Tasks*

*Nonsymbolic number discrimination.* This task taps into the ANS, requiring participants to quickly discriminate between two sets of dots (Piazza et al., 2010; Price et al., 2007). Two sets of black dots, randomly scattered, ranging from 2 to 8 dots within each set, were displayed simultaneously on a computer screen. Each singular dot had a diameter of 9 mm, and the sets were separated by a vertical line 2 mm thick. The objective in this task was to estimate and decide, as quickly as possible while trying to minimize the error rate, which of the two sets contained more dots. The exposure time of the stimuli (i.e., the sets of dots) was dependent on the response time of the participant. Thus, the sets were visually exposed to the participant until the participant responded by pressing either the A key, to indicate that the left set was more numerous, or the asterisk key, to indicate that the right set was more numerous. The key mappings were evidently assigned to spatially correspond to the visual arrays of dots. Prior to each stimulus item, the screen was blank for 1,000 ms. Five different set comparisons were used: 3 versus 4 dots, 4 versus 5 dots, 5 versus 6 dots, 5 versus 7 dots, and 6 versus 8 dots. Each set comparison was presented three times, which resulted in a net sum of trials to 15. Right before the actual trials, the participants were given four practice trials to familiarize themselves with the conditions and the general nature of the task. Since the stimulus exposure lasted until the participants made a decision and pressed the corresponding key, the error rate was very low (3%). Hence, only the response time was used as the dependent measure. The Cronbach's alpha reliability coefficient calculated on the current sample was established to be .90.

*One-digit magnitude comparison.* Since children with DD tend to perform poorly when they have to select the numerically larger of two Arabic numerals, which requires activation of the magnitude representations associated to the two numerals (Iuculano et al., 2008; Landerl et al., 2004; Landerl et al., 2009; Landerl & Kölle, 2009; Rousselle & Noël, 2007), we administered this task together with the nonsymbolic number discrimination task to investigate the mapping of the ANS and the symbolic system to see which aspect of number processing may be implicated or intact in the different groups.

Two Arabic one-digit numerals ranging from 1 to 9 (printed in Arial 40-point font) were simultaneously and horizontally displayed on a computer screen, and the center-to-center distance between the two numerals was 10 mm. The objective in this task was to decide which of the two numerals was the numerically larger one and respond with either the A key, corresponding to the left numeral, or the asterisk key, corresponding to the right numeral, which is consistent with prior tests in the battery, and the rationale behind the key mapping is evidently the same. Before each trial, a fixation cross was displayed for 1,000 ms, after which two digits were presented and remained exposed to the participant until he or she pressed a button. Two numerical distances were used, 1 (e.g., 2-3, 5-6) and 4 to 5 (e.g., 1-6, 4-9, 3-7), and each pair was presented twice, resulting in a total of 32 trials. The response times and errors were registered for each trial by the software program, and only response times for correct responses were recorded and used in the analysis. Also, responses in which the response times were less than 200 ms were discarded and considered guesses or false starts (< 0.5% of all trials), and response times exceeding 2 *SD* of a participant's mean response time were excluded as well (cf. Ashkenazi et al., 2009; Landerl & Kölle, 2009). The remaining correct responses within that time interval were used to calculate a mean response time for each condition. The mean response times and response accuracy were pooled into inverse efficiency measures for each participant; this measure was calculated by dividing the mean response time by the proportion of correct responses (i.e., accuracy; see Iuculano et al., 2008). The Spearman–Brown reliability calculated between the two numerical distance conditions (i.e., 1 and 4–5) was $r_{sh}$ = .87.

*Two-digit magnitude comparison.* This task was essentially identical to the one-digit numerical magnitude comparison task described above, with the only exception and conceptual difference being that the stimuli now consisted of two-digit pairs rather than one-digit pairs. The numerical distance between the pairs was either 1 or 5 (e.g., 21-22, 46-47, 31-36, 54-59). The Spearman–Brown reliability calculated between the two numerical distance conditions (i.e., 1 and 5) was $r_{sh}$ = .90.

*One- and two-digit naming.* The object of this task was, as the name implies, to quickly name presented numerals. Two sheets of paper were used in this experiment, and in the one-digit condition seven rows of the numerals 1 to 9 was printed in black ink (Times 28-point font). Each numeral appeared once in every row, resulting in a 63 numerals in all. The participant was told to name each numeral as fast as possible without making any errors. Throughout the trial, a stopwatch was used to measure the total time it took for the participant to name all the 63 numerals, and if any error was made by the child, the experimenter registered it accordingly. The mean response time it took for the participant to name all the numerals was used as the dependent measure. The two-digit numeral condition consisted of six rows and 27 numerals, and each numeral appeared twice. The order of presentation was identical for all participants, beginning with the one-digit condition with the two-digit condition administered immediately thereafter. The correlation between the one-digit numeral condition and the two-digit numeral condition was $r$ = .76.

*Number line estimation task.* This task was used to tap the symbolic mental number line that rests on the ANS; however, the task also taps the symbolic system and the mapping between them (Geary et al., 2007; LeFevre et al., 2010; Piazza, 2010; Siegler & Opfer, 2003; Von Aster & Shalev, 2007). The task was to indicate with a pencil where a particular number would go on a 0 to 1,000 number line, similar to the procedure used by Landerl et al. (2009). The decision to use the 0 to 1,000 line was made due to the suggestion by Booth and Siegler (2008) that children shift to a linear number line estimation of 0 to 1,000 between second and fourth grades. The material consisted of a booklet with 9 pages with two horizontal 21 cm number lines on each page. Each one of the 16 experimental problems had the number 0 printed at the left end of the line and the number 1,000 printed at the right end of the line. The number to be estimated was presented 2 cm above the center of the line. The children were first presented with two demonstration and practice problems (on page 1) that had the number 0 printed at the left end of the line and the numbers 10 and 500, respectively, printed at the right end of the line. After the two demonstration and practice problems, the children were instructed to solve the remaining problems in the same way as the demonstration and practice problems. The 16 numbers used were 2, 7, 12, 19, 28, 71, 86, 103, 230, 390, 475, 582, 690, 754, 810, and 962. Each child received one of four presentation orderings of the numbers, with the orderings counterbalanced. Accuracy of estimates in relation to a perfect linear function (i.e., percentage absolute error) was used as the dependent measure. Each child's percentage absolute error for each item was calculated by dividing the difference between the target numeral/number and the estimated numeral/number with the scale of the number line (number estimate – actual number / scale of number line). The mean of 16% absolute errors was used as a measure of the child's estimation accuracy, that is, the quality of the child's symbolic mental number representational system. The present Cronbach's alpha coefficient was established to be .90.

## *General Procedure*

The study was conducted over two separate sessions, each lasting approximately 120 min and including a break mid-session, both performed within a temporal window of one month. The two sessions were divided into one group session and one individual test session, where all the tests were administered in the same order for all participants in the study. Instructions regarding the tasks were given orally, although they were read aloud from a printed manuscript to ensure that every participant was given identical information. After instructions were provided and prior to the testing phase, at least one practice trial for each test was performed to eliminate any misconceptions about the nature of the upcoming task. The tasks that were administered through a computer were run on an Apple PowerMac™ laptop, and the presentation software was SuperLab PRO 4.5. The individual test session contained the following tasks: visual matrix span, color naming/Stroop, nonsymbolic number discrimination, listening span, numerical magnitude comparison, and number naming. During the group session, the following tasks were administered: screening test of arithmetic calculation, *Raven's Standard Progressive Matrices*, arithmetic problem solving (not reported here), screening test of reading, and number line estimation.

# Results

ANCOVAs were primarily used to test the stipulated hypotheses, although occasional ANOVAs were used as well. The Tukey–Kramer test was used as a post hoc testing procedure. Performances (raw scores) on Raven's test and the reading task were used as a covariates in all ANCOVAs to control for group differences in fluid IQ and reading, which have been demonstrated above. Means and standard deviations for all tasks used in the study for the AFD, GD, and the TA groups are displayed in Table 2.

## *Nonsymbolic Number Discrimination*

An ANCOVA with IQ and reading as covariates and post hoc testing revealed that the GD group performed significantly slower than the TA group on the nonsymbolic number discrimination task, $F(2, 72) = 3.74$, $p = .029$, partial

**Table 2.** Descriptive Data for the Number Processing Task for the AFD Group, the GD Group, and the TA Group.

| | AFD | | GD | | TA | |
|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Nonsymbolic number discrimination | 1.47 | 0.61 | 1.71 | 0.94 | 0.95 | 0.24 |
| One-digit naming | 34.81 | 7.67 | 40.53 | 16.61 | 27.63 | 5.17 |
| Two-digit naming | 61.38 | 17.76 | 72.97 | 25.92 | 44.37 | 10.00 |
| One-digit magnitude comparison | 0.95 | 0.28 | 0.98 | 0.17 | 0.66 | 0.11 |
| Two-digit magnitude comparison | 1.38 | 0.44 | 1.46 | 0.40 | 0.91 | 0.14 |
| Problem size effect | 0.43 | 0.22 | 0.48 | 0.34 | 0.25 | 0.09 |
| Number line estimation (error) | 9.22 | 5.27 | 12.48 | 5.88 | 4.47 | 2.22 |

*Note.* AFD = arithmetic fact dyscalculia; GD = general dyscalculia; TA = typical achievers.

$\eta^2 = .09$, whereas the AFD group performed on par with the TA group ($p > .05$). To examine if the slower performance of the GD group might have arisen from a general slowness as indicated by their performance on the color naming task, a second ANCOVA was computed with this task as an additional covariate. Controlling for performance on the color naming task as well as IQ and reading did not eliminate the slower performance of the GD group, $F(2, 71) = 3.33$, $p = .043$, partial $\eta^2 = .08$.

## *Digit Naming*

An ANCOVA with IQ as a covariate performed on the one-digit naming task revealed a significant group effect, $F(2, 73) = 8.65$, $p < .001$, partial $\eta^2 = .19$. The Tukey–Kramer tests showed that the GD group performed slower than the TA group, but the AFD group performed as fast as the TA group. However, when reading was included as an additional covariate, the group effect disappeared ($p > .05$).

An ANCOVA with IQ and reading as covariates and post hoc testing performed on the two-digit naming task showed that the AFD group performed as fast as the controls ($p > .05$), whereas the GD group performed slower than the controls, $F(2, 72) = 3.67$, $p = .03$, partial $\eta^2 = .09$, but including performance on the color naming task as a covariate in addition to IQ and reading eliminated the slower performance of the GD group ($p > .05$).

## *Digit Magnitude Comparison*

Scores on the one-digit and two-digit comparison tasks were analyzed by two separate 3 (group) × 2 (distance) mixed ANCOVAs with Raven's test and reading as covariates.

On the one-digit task, the ANCOVA yielded a significant distance effect, $F(1, 72) = 4.50$, $p = .037$, partial $\eta^2 = .06$ (Distance 1: $M = 0.94$; Distance 4–5: $M = 0.79$), and a significant group effect, $F(2, 72) = 11.64$, $p < .001$, partial $\eta^2 = .24$, but no group by distance interaction ($p > .05$). On the two-digit task, only a significant group effect emerged, $F(2, 72) = 9.26$, $p < .001$, partial $\eta^2 = .20$, not a distance effect or interaction effect ($p > .05$). However, when excluding IQ and reading from the ANOVA, an effect of distance emerged, $F(1, 74) = 10.21$, $p = .002$, partial $\eta^2 = .12$ (Distance 1: $M = 1.28$; Distance 5: $M = 1.21$), but not an interaction effect ($p > .05$). Post hoc tests showed that the AFD group and the GD group performed the one-digit and two-digit comparison tasks slower than did the controls.

To examine if the significant effects of group on the digit comparison tasks remained after controlling for IQ, reading, and scores on the one-digit and two-digit naming tasks, two additional ANCOVAs were performed. The two ANCOVAs revealed that the AFD and GD groups still performed slower than the TA group on the one-digit task, $F(2, 71) = 7.04$, $p = .002$, partial $\eta^2 = .16$, and the two-digit task, $F(2, 71) = 9.77$, $p < .001$, partial $\eta^2 = .21$.

## *Problem Size Effect*

To check if the three groups demonstrated the classical problem size effect to the same degree, an additional 3 (group) × 2 (one-digit vs. two-digit numerals) mixed ANCOVA with IQ as a covariate was performed (i.e., group × interactions) on the overall performance of the one-digit and two-digit comparison tasks (see Table 2). A significant problem size effect, $F(1, 73) = 4.61$, $p = .03$, partial $\eta^2 = .06$, was obtained, as was, more important, a significant group × problem size interaction effect, $F(2, 73) = 6.71$, $p = .002$, partial $\eta^2 = .16$.

To further examine the interaction, a problem size effect measure was calculated for each child by subtracting the performance on the one-digit task from the two-digit task. An ANCOVA with Raven's test as a covariate and post hoc testing performed on this measure revealed that the AFD group and the GD group displayed a larger problem size effect, $F(2, 73) = 6.72$, $p = .002$, partial $\eta^2 = .16$, than the controls (see Table 2). Thus, the AFD and GD groups were more influenced by the numerical size of the digits than the

TA group. However, the larger problem size effect displayed by the AFD and GD children disappeared when controlling for reading as well as IQ ($p > .05$).

### Number Line Estimation

An ANCOVA with Raven's test and reading as covariates demonstrated a significant group effect, $F(2, 72) = 6.71$, $p = .002$, partial $\eta^2 = .16$, that was a result of higher percentage absolute error scores of the AFD and the GD groups compared to the TA group. The number line estimation task taps the symbolic mental number line, founded on the ANS, but it also taps the symbolic system and the mapping between the two systems (Geary et al., 2007; LeFevre et al., 2010; Piazza, 2010; Siegler & Opfer, 2003). Hence, an additional ANCOVA with the overall performance of the one-digit and two-digit comparison tasks included as covariates was performed to examine if the poorer performance of the AFD and GD groups remained after controlling for the influence of symbolic number system and the mapping between the systems as well as IQ and reading. The ANCOVA with the overall digit comparison measure revealed that the GD group still performed poorer than the TA group, whereas the AFD group now performed on a par with the TA group, $F(2, 71) = 4.36$, $p = .016$, partial $\eta^2 = .11$.

## Discussion

In the present study, the defective ANS hypothesis and the access deficit hypothesis were tested in children with different mathematical deficits: AFD and GD. The aim was to gain a more comprehensive understanding of DD by investigating if the underlying origins of DD in children with different profiles of mathematical deficits are the same or different. The results are discussed using the two hypotheses in turn as a platform, followed by a conclusion.

### Children With GD Have a Deficit in the Innate Approximate Number System

The defective ANS hypothesis is premised on the notion that humans are born with a preverbal ability to represent quantities approximately and that this ability constitutes the foundation for development of the symbolic number system used for arithmetic (e.g., Butterworth, 1999; Feigenson et al., 2004; Piazza, 2010). Thus, the defective ANS hypothesis predicts that both nonsymbolic and symbolic number processing is implicated in DD, and the behavioral pattern displayed by the GD group on the nonsymbolic number task, the digit magnitude comparison tasks, and the number line estimation task is congruent with this notion.

Very direct and strong support for the ANS hypothesis is demonstrated by the GD group's significantly slower performance on the nonsymbolic discrimination task, even when controlling for IQ, reading, and speed of access to long-term memory information (color naming). This finding is consistent with earlier work on DD (cf. Landerl et al., 2009; Mazzocco et al., 2011; Mejias et al., 2012; Mussolin et al., 2010; Piazza et al., 2010; Price et al., 2007). Further support for the ANS hypothesis is provided since performance on the one- and two-digit comparison tasks was significantly slower in the GD group even when controlling for IQ, reading, and scores on the one-digit and two-digit naming tasks, which would control for the influence of the symbolic number system. Another interesting aspect of this symbolic comparison task is that children with GD showed a larger problem size effect than the TA children, indicating that they have noisier number representations (i.e., inferior ANS acuity).

Another important finding in line with the defective ANS hypothesis is that the GD group performed significantly worse than the TA group on the number line estimation task, even when controlling for influence of the symbolic system and the mapping between the ANS and the symbolic number system by including digit comparison performance as a covariate as well as IQ and reading (Geary et al., 2007; LeFevre et al., 2010; Piazza, 2010; Siegler & Opfer, 2003). The number line estimation task requires that participants translate between numerical and spatial representations, and the task measures the linearity and sophistication of the mental number line of the participants (Siegler & Opfer, 2003). In its original form, it is believed to tap into several abilities, such as the ANS, the symbolic system, and spatial abilities that together are responsible for the mapping process and the subsequent mental number line formation (Von Aster & Shalev, 2007). By controlling for IQ, reading, and symbolic processing, we isolated the effect of the ANS and compared between groups; the GD showed weaker performance, indicating that ANS is implicated in this subgroup of DD. Thus, on a neurocognitive level, it is likely that this subgroup has a primary deficit in the IPS resulting in a deficit in the ANS on the cognitive level, which then affects many areas of number processing. For instance, it is possible that this deficit subsequently affects symbolic number processing by corrupting the mapping process between the nonsymbolic and symbolic systems, because the symbols are mapped onto the already undermined nonsymbolic system, yielding the impaired performance on the symbolic number comparison task. One should, however, be careful in drawing firm conclusions about the direction of causation since it is also conceivable that impaired ANS acuity is the *result* of a deficient symbolic and exact manipulation of numbers, which is an idea advocated by Noël and Rousselle (2011). Other research suggests otherwise, however, where research on preverbal infants and ANS acuity shows that infants who made finer nonsymbolic number discriminations at 6 months of age also showed superior and sharper ANS acuity at 9 months of age (Libertus & Brannon, 2010). Also, Mazzocco et al. (2011) found that ANS acuity at age 3 or 4 years is predictive of standardized math scores at ages 5 or 6, thereby showing an association between ANS acuity and math proficiency prior to any formal math instruction where children would supposedly be exposed to symbolic and exact number systems that, in turn, would affect and weaken the ANS acuity. It is also plausible that ANS acuity and mathematical experience have a bidirectional relationship, but that ANS deficits probably precede symbolic number processing impairments and subsequent mathematical difficulties.

Nevertheless, together these three findings indicate that children with GD have impairment in the acuity of the ANS (Landerl et al., 2009; Mazzocco et al., 2011; Piazza et al., 2010). Thus, a fuzzy or less precise ANS should make it more difficult to discriminate between sets of numerosities and magnitudes activated by the symbols (i.e., Arabic numbers) and impede the acquisition and learning of adequate basic arithmetic skills such as multidigit calculation and arithmetic fact retrieval (Dehaene, 1992, 2011; Feigenson et al., 2004; Piazza, 2010). The behavioral pattern displayed by this subgroup matches the profile of primary DD (Price & Ansari, 2013) and other conventional notions of DD, which is a condition with a core deficit in the innate number sense (Dehaene, 2011; Piazza, 2010). It is also congenial with Butterworth (2005) and *numerosity coding*, which is also a cognitive component responsible for the cognitive representations of numerosities akin to the ANS.

Most studies that have found a deficit in nonsymbolic number processing in children with DD have done so in children between 8 and 10 years of age (e.g., Landerl et al., 2009; Piazza et al., 2010), and only a few have done studies on older children with DD (e.g., Mazzocco et al., 2011). The children in our study were 11 to 13 years old, thus showing that the ANS deficit found in younger children with DD in previous research also applies to slightly older children as well.

### *Children With AFD Have an Access Deficit*

The main prediction of the access deficit hypothesis is that individuals with DD will display difficulties on symbolic number tasks while showing entirely intact nonsymbolic number processing. With respect to the AFD group, this is exactly what the current findings demonstrate: The AFD group showed poor performance compared to the TA group on the two-digit comparison tasks, but they performed on par with the TA group on the nonsymbolic number discrimination task, which is completely in line with the aforementioned hypothesis. Furthermore, the AFD group performed significantly worse than the TA group on the number line estimation task when *not* controlling for the influence of the symbolic system and the mapping between this system and the ANS. However, when including digit comparison performance as a covariate, the AFD group performed on par with the TA group, suggesting that their poorer performance is primarily due to impairment in the connection between symbolic numbers and magnitude representations (De Smedt & Gilmore, 2011; Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Landerl & Kölle, 2009; Noël & Rousselle, 2011; Rousselle & Noël, 2007).

These findings regarding children with AFD favor the access deficit hypothesis but are not consistent with the defective ANS hypothesis. It is theoretically plausible that a deviant connection between the symbolic number system and the ANS could hamper the retrieval of arithmetic facts established in semantic long-term memory as it has been shown that fact retrieval first entails a symbol identification stage, followed by a digit magnitude comparison stage and finally a retrieval stage (Butterworth, Zorzi, Girelli, & Jonckheere, 2001). Theoretically, the digit comparison stage, which constrains the connection between the symbolic system and the ANS, could indeed constitute a bottleneck for children with AFD during arithmetic fact retrieval. Various neuroimaging studies indicate that children with DD display structural differences in terms of loss of gray matter volume in the IPS and frontal areas (Kaufmann, Wood, Rubinsten, & Henik, 2011) but also white matter tracts that connect these areas and likely play a role in the mapping process between symbols and their semantic content (Nieder, 2009). This pathophysiology would be congenial with the findings of Rousselle and Noël (2007) and their access deficit hypothesis. Another possibility is that the parietal circuit connecting the IPS with angular gyrus is damaged since the angular gyrus is thought to subserve skilled arithmetic fact retrieval (Dehaene, Piazza, Pinel, & Cohen, 2003; Zamarian, Ischebeck, & Delazer, 2009). Price and Ansari (2011) noted that merely glancing at Arabic digits elicited stronger activation in the angylar gyrus compared with nonsensical symbols, and Ansari (2008) suggested that the angylar gyrus subserves automatic mapping between mathematical symbols and their semantic referents. Moreover, gains of arithmetic competence and expertise have reflected a shift from frontal areas to more posterior ones, as well as a shift from IPS to angular gyrus, probably reflecting increased reliance on rapid access to arithmetic facts, rather than laborious calculation procedures (Zamarian et al., 2009). Individuals with this particular pathophysiology may not display any problems with working memory tasks due to their potentially intact and unaffected IPS and/or prefrontal areas more traditionally thought of as integral to working memory processing and numerical processing (Rubinsten & Henik, 2009). A neurocognitive deficit originating in the parietal circuit connecting the IPS and angular gyrus would therefore also be in line the access deficit hypothesis.

The considerations concerning the neurocognitive underpinnings responsible for the observed behavioral deficits in the current study are speculative, but by taking different studies across levels of analysis (i.e., cognitive level, neurological level, etc.) into account, one might arrive at testable hypotheses. Hence, given that we have identified different subgroups of children with DD, each with their own cognitive profile, and providing support for De Visscher and Noël's (2013) proposed subtype of DD, the next step would be to investigate these subgroups using neuroimaging data to verify this categorization. The results from the current study also emphasize the need for careful deliberation when choosing which selection criteria to use when identifying children with DD to ensure that different subtypes of DD are not conflated, thereby obscuring the genuine underlying pathophysiologies. For instance, if we had adopted a selection procedure that exclusively relied on an arithmetic fact retrieval task to identify children with "pure" DD, as some researchers have done previously (e.g., Landerl et al., 2004; Mussolin et al., 2010), we would have mistakenly conflated both GD and AFD into a single heterogeneous sample of children that would have obscured the etiologies within that group. In addition, we used quite strict selection criteria, where children in the GD group performed at or below the bottom 5th percentile on both arithmetic tasks, and we believe that by using stringent cutoffs (below 10th percentile) a more homogeneous subgroup of children with mathematical difficulties is revealed, and that using more lenient criteria (11th–25th percentile) may lead to conflation of children with DD with low achievers of mathematical skills (Mazzocco et al., 2011). Mazzocco et al. (2011) found that low achievers did not differ from TA children on ANS tasks and that only children with pervasive DD (< 10th percentile) showed a weaker ANS acuity compared to low achievers (11th–25th percentiles), TA children (25th–95th percentiles), and high achievers (> 95th percentile). It is therefore likely that using more lenient cutoffs may result in heterogeneous samples with different cognitive profiles, which in turn makes it hard to identify the pathophysiology of DD and its subtypes.

Another important aspect to keep in mind when identifying children with DD is to carefully consider the actual screening tests used. Several of the studies on DD have employed a quite broad and complex amalgam of tests assessing mathematical skills, where aggregated performance on a multitude of tasks is used as a general measure and indicator of mathematical skill from which a variable bottommost percentile is estimated to suffer from DD (e.g., D'Amico & Passolunghi, 2009; Geary et al., 2008; Piazza et al., 2010). For example, Piazza et al. (2010) used Arabic number reading, Arabic number writing, number repetition, symbolic number discrimination, number insertion, arithmetic calculation, arithmetic fact retrieval, oral calculation, and complex written calculation to yield a composite measure of math ability. Although this approach of casting a wide net may be highly effective in identifying children with mathematical difficulties, which is certainly desirable in many circumstances, it also enables the possibility that some children with different strengths and weaknesses in mathematical or cognitive skill may be able to avoid being identified altogether by relying on individual strengths and through compensatory abilities make the cutoff in the end. For example, in the number repetition task employed by Piazza et al. (2010), children with superior phonological skill and auditory working memory capacity may excel at this task while showing poor number discrimination ability. Nevertheless, the use of complex test batteries of arithmetic ability likely invites heterogeneity. In our study we used only two quite simple arithmetic tasks to identify children with DD. We do not claim that our procedure is superior to the aforementioned ways of estimating mathematical skills, but we want to raise awareness that the choices made will have implications regarding the population of children who ultimately will—or will not—make the cut.

The findings from the current study may also have implications for practitioners in the educational setting. Given that we have identified subtypes of DD, it is likely that different interventional instruments should target different subtypes. Children who struggle with rapid retrieval of arithmetic facts often do not substantially improve across early school years (Geary, 2004), but some children may benefit from practice on time-constrained retrieval of arithmetic facts that forces them to not fall back on laborious counting strategies (Gersten, Jordan, & Flojo, 2005). Gersten et al. (2005) suggested that teaching children backup strategies, such as resorting to known nearby arithmetic facts to arrive at an answer, may be productive. Children with GD, on the other hand, may need interventions that target their specific deficits, namely the ANS, subserving the development of a mental number line. These aspects of number sense should be teachable (Gersten et al., 2005), and promising research indicates that the ANS is malleable (DeWind & Brannon, 2012). Feedback training improved adults' ANS acuity and numerical precision, although it remains an open question whether this improvement would transfer to other mathematical domains (DeWind & Brannon, 2012), and recent work by Park and Brannon (2013) found that training of the ANS actually improved math proficiency in adults, suggesting that interventions targeting the ANS could benefit children with GD. In the same vein, Feigenson, Libertus, and Halberda (2013) suggested that increased ANS acuity may serve as a useful aid during symbolic computations, which may allow children to detect gross errors and arrive at reasonable answers during problem solving.

Although we have tried to emphasize the heterogeneity and complexity of dyscalculia, there is most certainly a neurocognitive profile that can be labeled "pure" DD where number sense is the primary and circumscribed deficit, but this neurocognitive profile is most likely applicable to only a minority of children with DD, where multiple cognitive deficits such as attention deficits, executive functioning, or reading difficulties are often simultaneously manifest in these children. We suggest that the heterogeneity of symptoms and difficulties, as well as the screening procedures used to detect them, need to be taken into account in future research.

## Conclusion

The current study provides evidence demonstrating that the origins of DD in children with different profiles of mathematical deficit diverge. Children with GD have impairment in the ANS, whereas children with general AFD suffer from an access deficit, that is, a deficit in the connection between the symbolic number system and the innate ANS. This finding is consistent with Rubinsten and Henik's (2009) proposal that DD might be caused by several different pathophysiologies, that in parallel give rise to deficient number processing in a given individual, or that different individuals display different neurocognitive profiles that give rise to the unique mathematical symptoms. We urge researchers within the field to carefully select which screening procedures to use, with respect to both cutoff criteria and tests of arithmetic abilities.

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### References

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Arlington, VA: Author.

Andersson, U. (2010). Skill development in different components of arithmetic and basic cognitive functions: Findings from a three-year longitudinal study of children with different types of learning difficulties. *Journal of Educational Psychology*, *102*, 115–134. doi:10.1037/a0016838

Ansari, D. (2008) Effects of development and enculturation on number representation in the brain. *Nature Reviews Neuroscience*, *9*(4), 278-291. doi:10.1038/nrn23

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2009). Numerical distance effect in developmental dyscalculia. *Cognitive Development*, *24*, 387–400. doi:10.1016/j.cogdev.2009.09.006

Barbaresi, W. J., Katusic, S. K., Colligan, R. C., Weaver, A. L., & Jacobsen, S. J. (2005). Math learning disorder: Incidence in a population-based birth cohort, 1976-82, Rochester, Minn. *Ambulatory Pediatrics*, *5*, 281–289. doi:10.1367/A04-209R.1

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016–1031. doi:10.1111/j.1467-8624.2008.01173.x

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of Arabic numerals. *Cognition*, *118*, 32–44. doi:10.1016/j.cognition.2010.09.005

Butterworth, B. (1999). *The mathematical brain*. London, UK: Macmillan.

Butterworth, B. (2005). Developmental dyscalculia. In J. I. D Campbell (Ed.), *Handbook of mathematical cognition* (pp. 455–467). New York, NY: Psychology Press.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science*, *6033*, 1049–1053. doi:10.1126/science.1201536

Butterworth, B., Zorzi, M., Girelli, L., & Jonckheere, A. R. (2001). Storage and retrieval of addition facts: The role of number comparison. *Quarterly Journal of Experimental Psychology*, *54A*, 1005–1029. doi:10.1080/713756007

D'Amico, A., & Passolunghi, M. C. (2009). Naming speed and effortful and automatic inhibition in children with arithmetic learning disabilities. *Learning & Individual Differences*, *19*, 170–180. doi:10.1016/j.lindif.2009.01.001

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*, 1–42. doi:10.1016/0010-0277(92)90049-N

Dehaene, S. (2011). *The number sense*. New York, NY: Oxford University Press.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*, 487–506. doi:10.1080/02643290244000239

de Hevia, M. D., Vallar, G., & Girelli, L. (2006). Numbers and space: A cognitive illusion? *Experimental Brain Research*, *168*, 254–264. doi:10.1007/s00221-005-0084-0

Denckla, M. B., & Rudel, R. G. (1976). Rapid automatized naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471–479. doi:10.1016/0028-3932(76)90075-0

De Smedt, B., & Gilmore, C. K. (2011). Numerical magnitude processing in first graders with mathematical difficulties. *Journal of Experimental Child Psychology*, *108*, 278–292. doi:10.1016/j.jecp.2010.09.003

Desoete, A., Ceulemans, A., De Weerdt, F., & Pieters, S. (2012). Can we predict mathematical learning disabilities from symbolic and non-symbolic comparison tasks in kindergarten? Findings from a longitudinal study. *British Journal of Educational Psychology*, *82*, 64–81. doi:10.1348/2044-8279.002002

De Visscher, A., & Noël, M.-P. (2013). A case study of arithmetic facts dyscalculia caused by a hypersensitivity-to-interference in memory. *Cortex*, *49*, 50–70. doi:10.1348/2044-8279.002002

DeWind, N. K., & Brannon, E. M. (2012). Malleability of the approximate number system: effects of feedback and training. *Frontiers in Human Neuroscience*, *6*, 68. doi:10.3389/fnhum.2012.00068

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 309–314. doi:10.1016/j.tics.2004.05.002

Feigenson, L., Libertus, M. E., & Halberda, J. (2013). Links between the intuitive sense of number and formal mathematics ability. *Child Development Perspectives*, *7*, 74–79. doi:10.1111/cdep.12019

Gallistel, C., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, *44*, 43–74. doi:10.1016/0010-0277(92)90050-R

Geary, D. C. (2004) Mathematics and learning disabilities. *Journal of Learning Disabilities*, *37*(1), 4-15. doi:10.1177/00222194040370010201

Geary, D. C., Hoard, M. K., Byrd-Craven, J., Nugent, L., & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development*, *78*, 1343–1359. doi:10.1111/j.1467-8624.2007.01069.x

Geary, D. C., Hoard, M. K., & Hamson, C. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology*, *74*, 213–239. doi:10.1006/jecp.1999.2515

Geary, D. C., Hoard, M. K., Nugent, L., & Byrd-Craven, J. (2008). Development of number line representations in children with mathematical learning disability. *Developmental Neuropsychology*, *33*, 277–299. doi:10.1080/87565640801982361

Gelman, R., & Butterworth, B. (2005). Number and language: How are they related? *Trends in Cognitive Sciences*, *9*, 6–10. doi:10.1016/j.tics.2004.11.004

Gersten, R., Jordan, N. C., & Flojo, J. R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities*, *38*, 293–304. doi:10.1177/00222194050380040301

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the “number sense”: The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*, 1457–1465. doi:10.1037/a0012682

Henik, A., Rubinsten, O., & Ashkenazi, S. (2011). The “where” and “what” in developmental dyscalculia. *Clinical Neuropsychologist*, *25*, 989–1008. doi:10.1080/13854046.2011.599820

Holloway, I. D., & Ansari, D. (2008). Domain-specific and domain-general changes in children’s development of number comparison. *Developmental Science*, *11*, 644–649. doi:10.1111/j.1467-7687.2008.00712.x

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children’s mathematics achievement. *Journal of Experimental Child Psychology*, *103*, 17–29. doi:10.1016/j.jecp.2008.04.001

Iuculano, T., Tang, J., Hall, C. W. B., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science*, *11*, 669–680. doi:10.1111/j.1467-7687.2008.00716.x

Jordan, N. C., & Hanich, L. B. (2003). Characteristics of children with moderate mathematics deficiencies: A longitudinal perspective. *Learning Disabilities Research & Practice*, *18*, 213–221. doi:10.1111/1540-5826.00076

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology*, *85*, 103–119. doi:10.1016/S0022-0965(03)00032-8

Jordan, N. C., Kaplan, D., & Hanich, L. B. (2002). Achievement growth in children with learning difficulties in mathematics: Findings of a two-year longitudinal study. *Journal of Educational Psychology*, *94*, 586–597. doi:10.1037//0022-0663.94.3.586

Jordan, N. C., & Montani, T. O. (1997). Cognitive arithmetic and problem solving: A comparison of children with specific and general mathematics difficulties. *Journal of Learning Disabilities*, *30*, 624–634. doi:10.1177/002221949703000606

Kaufmann, L., Wood, G., Rubinsten, O., & Henik, A. (2011). Meta-analyses of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation. *Developmental Neuropsychology*, *36*, 763–787. doi:10.1080/87565641.2010.549884

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition*, *93*, 99–125. doi:10.1016/j.cognition.2003.11.004

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2009). Dyslexia and dyscalculia: Two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology*, *103*, 309–324. doi:10.1016/j.jecp.2009.03.006

Landerl, K., & Kölle, C. (2009). Typical and atypical development of basic numerical skills in elementary school. *Journal of Experimental Child Psychology*, *103*, 546–565. doi:10.1016/j.jecp.2008.12.006

Le Corre, M., & Carey, S. (2007). One, two, three, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. *Cognition*, *105*, 395–438. doi:10.1016/j.cognition.2006.10.005

LeFevre, J. A., Fast, L., Skwarchuk, S., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development*, *81*, 1753–1767. doi:10.1111/j.1467-8624.2010.01508.x

Libertus, M. E., & Brannon, E. M. (2010). Stable individual differences in number discrimination in infancy. *Developmental Science*, *13*, 900–906. doi:10.1111/j.1467-7687.2009.00948.x

Malmquist, E. (1977). *Reading and writing difficulties in children. Analysis and treatment*. Lund, Sweden: Gleerups.

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*, 1224–1237. doi:10.1111/j.1467-8624.2011.01608.x

Mejias, S., Mussolin, C., Rousselle, L., Grégoire, J., & Noël, M.-P. (2012). Numerical and nonnumerical estimation in children with and without mathematical learning disabilities. *Child Neuropsychology*, *18*, 550–575. doi:10.1080/09297049.2011.625355

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*, 1519–1520. doi:10.1038/2151519a0

Mundy, E., & Gilmore, C. K. (2009). Children’s mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology*, *103*, 490–502. doi:10.1016/j.jecp.2009.02.003

Mussolin, C., Mejias, S., & Noël, M.-P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition*, *115*, 10–25. doi:10.1016/j.cognition.2009.10.006

Nieder, A. (2009). Prefrontal cortex and the evolution of symbolic reference. *Current Opinion in Neurobiology*, *19*, 99–108. doi:10.1016/j.conb.2009.04.008

Noël, M.-P., & Rousselle, L. (2011). Developmental changes in the profiles of dyscalculia: An explanation based on a double exact-and-approximate number representation model. *Frontiers in Human Neuroscience*, *5*, 165. doi:10.3389/fnhum.2011.00165

Park, J., & Brannon, E. M. (2013). Training the approximate number system improves math proficiency. *Psychological Science*, *24*, 2013–2019. doi:10.1177/0956797613482944

Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences*, *14*, 542–551. doi:10.1016/j.tics.2010.09.008

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., . . . Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*, 33–41. doi:10.1016/j.cognition.2010.03.012

Previtali, P., de Hevia, M. D., & Girelli, L. (2010). Placing order in space: The SNARC effect in serial learning. *Experimental Brain Research*, *201*, 599–605. doi:10.1007/s00221-009-2063-3

Price, G. R., & Ansari, D. (2011). Symbol processing in the left angular gyrus: Evidence from passive perception of digits. *NeuroImage*, *57*, 1205–1211. doi:10.1016/j.neuroimage.2011.05.035

Price, G. R., & Ansari, D. (2013). Dyscalculia: Characteristics, causes, and treatments. *Numeracy*, *6*, 2. doi:http://dx.doi.org/10.5038/1936-4660.6.1.2

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, *17*, R1042–R1043. doi:10.1016/j.cub.2007.10.013

Raven, J. C. (1976). *Standard progressive matrices*. Oxford, UK: Oxford Psychologists Press.

Rousselle, L., & Noël, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, *102*, 361–395. doi:10.1016/j.cognition.2006.01.005

Rubinsten, O., & Henik, A. (2009). Developmental dyscalculia: Heterogeneity might not mean different mechanisms. *Trends in Cognitive Sciences*, *13*, 92–99. doi:10.1016/j.tics.2008.11.002

Russell, R. L., & Ginsburg, H. P. (1984). Cognitive analysis of children's mathematical difficulties. *Cognition and Instruction*, *1*, 217–244.

Rykhlevskaia, E., Uddin, L. Q., Kondos, L., & Menon, V. (2009). Neuroanatomical correlates of developmental dyscalculia: Combined evidence from morphometry and tractography. *Frontiers in Human Neuroscience*, *3*, 51. doi:10.3389/neuro.09.051.2009

Shalev, R. S. (2007). Prevalence of developmental dyscalculia. In D. B. Berch & M. M. M. Mazzocco (Eds.), *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities* (pp. 49–60). Baltimore, MD: Brookes.

Siegler, R., & Opfer, J. (2003). The development of numerical estimation: evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–243. doi:10.1111/1467-9280.02438

Temple, C. M. (1991). Procedural dyscalculia and number fact dyscalculia: Double dissociation in developmental dyscalculia. *Cognitive Neuropsychology*, *8*, 155–176. doi:10.1080/02643299108253370

Temple, C. M., & Sherwood, S. (2002). Representation and retrieval of arithmetical facts: Developmental difficulties. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, *55A*, 733–752. doi:10.1080/02724980143000550

Träff, U. (2012). *Test battery for the identification and diagnosis of learning disabilities in mathematics: Grades* 3–6. Linköping, Sweden: Linköping University, Department of Behavioural Sciences and Learning.

Von Aster, M., & Shalev, R. (2007). Number development and developmental dyscalculia. *Developmental Medicine & Child Neurology*, *49*, 868–873. doi:10.1111/j.1469-8749.2007.00868.x

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In D. Coch, G. Dawson, & K. Fischer (Eds.), *Human behavior, learning, and the developing brain: Atypical development* (pp. 212–238). New York, NY: Guilford.

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, *24*, 220–251. doi:10.1016/0010-0285(92)90008-P

Wynn, K. (1995). Origins of numerical knowledge. *Mathematical Cognition*, *1*, 35–60.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*, B1–B11. doi:10.1016/S0010-0277(99)00066-9

Zamarian, L., Ischebeck, A., & Delazer, M. (2009). Neuroscience of learning arithmetic—Evidence from brain imaging studies. *Neuroscience and Biobehavioral Reviews*, *33*, 909–925. doi:10.1016/j.neubiorev.2009.03.005