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Developmental Dyscalculia in Adults: Beyond Numerical Magnitude Impairment

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Abstract

Numerous studies have tried to identify the core deficit of developmental dyscalculia (DD), mainly by assessing a possible deficit of the mental representation of numerical magnitude. Research in healthy adults has shown that numerosity, duration, and space share a partly common system of magnitude processing and representation. However, in DD, numerosity processing has until now received much more attention than the processing of other non-numerical magnitudes. To assess whether or not the processing of non-numerical magnitudes is impaired in DD, the performance of 15 adults with DD and 15 control participants was compared in four categorization tasks using numerosities, lengths, durations, and faces (as non-magnitude-based control stimuli). Results showed that adults with DD were impaired in processing numerosity and duration, while their performance in length and face categorization did not differ from controls' performance. Our findings support the idea of a nonsymbolic magnitude deficit in DD, affecting numerosity and duration processing but not length processing.

Keywords

magnitude processing, dyscalculia, nonsymbolic estimation, numerosity, length, duration

Learning arithmetic and mathematics is a major objective of primary school, but many children face significant difficulties; of those children, 3% to 6% show a severe and persistent deficit, named *developmental dyscalculia* (DD; American Psychiatric Association, 2013), despite normal intelligence and an appropriate education environment. Understanding this learning impairment is thus an important societal concern and constitutes a major challenge for educational neurosciences. In recent decades, the learning of symbolic arithmetic and mathematics has been assumed to be grounded in an innate system dedicated to the processing of nonsymbolic number magnitudes that is present in infants and animals (e.g., Butterworth, 2005; Dehaene & Cohen, 2007; Wynn, 1998). Most studies investigating magnitude processing in DD have focused on the ability to process numerical magnitudes, mainly using comparison tasks in which the participants have to determine which of two Arabic numerals (symbolic) or collections of dots (nonsymbolic) was the larger or more numerous one. Accuracy and response latencies, often expressed through the numerical distance effect (i.e., the closer the numerosities, the longer and the more error prone the judgments; Moyer & Landauer, 1967), and the Weber fraction (i.e., measure of the smallest numerical change to a stimulus that can be reliably detected; Teghtsoonian & Teghtsoonian, 1978) have been used as measures of the ability to process numerical magnitudes. While most studies have reported weaker symbolic numerical processing capacities in children with DD compared to controls (e.g., De Smedt & Gilmore, 2011; Mussolin, Mejias, & Noël, 2010; Rousselle & Noël, 2007), the results are less clear-cut concerning nonsymbolic numerical magnitude processing (for a review, see De Smedt, Noël, Gilmore, & Ansari, 2013). For instance, compared to controls, children with DD have sometimes been found with a higher Weber fraction, thus indicating a lower acuity of nonsymbolic numerical processing (Piazza et al., 2010), and sometimes with a similar performance (De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007). These inconsistencies might be due to the age of the participants tested, as more robust differences have been found when participants are older (i.e., 10 years or older; Noël &

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Table 1. Studies Investigating Temporal and Spatial Processing in Children or Adults With Developmental Dyscalculia (DD).

Authors	Population	Tasks and range of stimuli	Results
Duration			
Cappelletti et al., 2011	Adults with DD (*N* = 12)	Time comparison of neutral stimuli primed by (a) non-numerical symbols (i.e., #) or (b) numbers (i.e., 1 or 9) (c) Time comparison of Arabic digits (range: 360–840 ms)	No difference between DD and controls for (a); DD less accurate than controls for (b) and (c)
Cappelletti et al., 2013	Adults with DD (*N* = 16)	Time comparison (range: 360–840 ms)	No difference between DD and controls
Gilaie-Dotan et al., 2014	Adults with DD (*N* = 6)	Time estimation (range: 12–13.2 s)	DD less accurate than controls
Hurks & Loosbroek, 2012	Children with DD (*N* = 13; mean age = 12 years old)	(a) Verbal time estimation (b) Time production (c) Time reproduction (range: 3–45 s)	No difference between DD and controls in (c); DD less accurate than controls in (a) and (b)
Skagerlund & Träff, 2014	Children with DD (*N* = 19; mean age = 10 years old)	Time comparison (range: 1,500–6,000 ms)	DD less accurate than controls
Vicario, Rappo, Pepi, Pavan, & Martino, 2012	Children with DD (*N* = 10; mean age = 8 years old)	(a) Time comparison (range: sub = 310–500 ms; supra = 1,280–1,520 ms) (b) Time reproduction (range: sub = 500–900 ms; supra = 1,500–1,900 ms)	No difference between DD and controls in (b); DD less accurate than controls in (a) for the subsecond intervals only
Length			
Ashkenazi & Henik, 2010	Adults with DD (*N* = 12)	Physical line bisection (range: 40–180 mm)	Absence of leftward bias (pseudoneglect) in DD
Cappelletti et al., 2013	Adults with DD (*N* = 16)	Length comparison of lines (range: 9.26°–11.32°)	No difference between DD and controls
Mussolin, Martin, & Schiltz, 2011	Adults with DD (*N* = 22)	Physical distance estimation task (range: 3–3.6 cm)	No difference between DD and controls

Rousselle, 2011). Alternatively, this variability in the results could stem from the differences in controlling the parameters varying together with numerosity, such as density, area, or contour (e.g., Gebuis & Reynvoet, 2012; Hurewitz, Gelman, & Schnitzer, 2006).

In addition to numerosity, the nonsymbolic magnitude system includes the processing of other dimensions, such as duration or space. Indeed, numerosity, space, and time are intermixed in the natural environment of animals and humans (e.g., Brannon & Roitman, 2003; Gallistel & Gelman, 2000) and have been shown to be already linked early in life (e.g., de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Lourenco & Longo, 2010). The idea of a generalized magnitude processing using a common metric system has been proposed in the ATOM model (a theory of magnitude; Walsh, 2003). An overlap of the areas underlying the processing of various magnitudes has indeed been supported by some brain imaging studies showing similar frontoparietal area activations when processing numerosities, durations, or lengths (e.g., Dormal, Dormal, Joassin, & Pesenti, 2012; Dormal & Pesenti, 2009; Hayashi et al., 2013; Tudusciuc & Nieder, 2009). Some behavioral and neurofunctional dissociations between these magnitudes have also been documented in neuropsychological and transcranial magnetic stimulation studies (e.g., Cappelletti, Freeman, & Cipolotti, 2009, 2011; Dormal, Andres, & Pesenti, 2008; Dormal, Grade, Mormont, & Pesenti, 2012; Rousselle, Dembour, & Noël, 2013; for reviews, see Dormal & Pesenti, 2012; Van Opstal & Verguts, 2013). Instead of a fully shared magnitude system, these studies suggest the coexistence of common and partially independent magnitude systems. In sum, certain aspects of magnitude processing are shared between these three magnitudes, and some are specific to one or two of them. One (or several) of these types of nonsymbolic magnitude processing is somehow linked to later mathematical abilities (Bueti & Walsh, 2009; Cohen Kadosh & Walsh, 2009; Dehaene & Cohen, 2007) and may be specifically altered in the case of DD.

Until now, few studies have explored the processing of duration or length in participants with DD (see Table 1). Regarding duration processing, a deficit was reported in a duration comparison task in which children with DD had to decide whether the duration of the test stimulus was longer or shorter than a referent stimulus just previously presented (Skagerlund & Träff, 2014; Vicario, Rappo, Pepi, Pavan, & Martino, 2012). Similarly, children (Hurks & Loosbroek, 2012) and adults with DD (Gilaie-Dotan, Rees, Butterworth, & Cappelletti, 2014) were less accurate than controls in a subsecond-interval estimation task. Yet this deficit in duration processing has not been replicated in other studies in adults with DD. Indeed, some studies reported the presence of a duration-processing impairment but only when the tasks involved numbers (i.e., when the participants were primed by an Arabic digit or when they had to judge the presentation duration of Arabic digits), while the performance in duration estimation was unimpaired when the stimuli were not numerals (Cappelletti et al., 2013; Cappelletti et al., 2011). This suggests that a deficit in processing numerical symbols may explain the difficulties in these specific duration tasks (Cappelletti et al., 2011).

As regards spatial processing, studies also led to contradictory findings in DD (see Table 1). While difficulties were observed in a line bisection task (Ashkenazi & Henik, 2010), accurate spatial judgements were observed in adults with DD during physical distance estimation (Mussolin, Martin, & Schiltz, 2011) and length comparison (Cappelletti et al., 2013) tasks. Currently, no firm evidence allows us to draw a conclusion regarding the integrity of length processing in DD, and further investigations are needed.

The main objective of the present study is to test the integrity of numerosity, length and duration processing in participants with DD in order to define whether this specific learning disability is associated with a specific impairment in number representation and processing or whether it is characterized by a larger deficit extending to other nonnumerical magnitudes. By using the same paradigm with the same participants, we were able to assess which nonsymbolic magnitude processing is impaired in DD, namely, a specific processing/mechanism dedicated to one dimension or a partially (i.e., common to two dimensions) or fully shared (i.e., common to all magnitudes) processing/mechanism. Two groups of participants (i.e., adults with DD and age-matched controls) were submitted to three magnitude categorization tasks (i.e., numerosity, length, and duration categorization) and one control task that did not involve any magnitude processing (i.e., face categorization). Importantly, we used carefully controlled sequential material (i.e., nonperiodic visual flashing dot sequences) excluding visuospatial confounding variables that are present when using simultaneously presented collections of dots (e.g., density, size of dots, occupied area, etc.). Furthermore, general cognitive processes, such as decision making, long-term memory load, or motor response mode, were controlled and matched across tasks.

Method

Participants

A total of 30 female volunteers—15 with DD (mean age: 26.3 ± 6.7 years) and 15 age-matched controls (mean age: 25.1 ± 5.5 years), $t(28) = 0.568$, *ns*—participated in the study. All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the Ethical Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain, Belgium. Written informed consent was given by each participant prior to the experiment.

Three tasks were used for the screening process. First, the *Advanced Progressive Matrices* test (Raven, Raven, & Court, 1998) was used to evaluate fluid intelligence. The participants had 30 min to answer to as many items as possible. Second, we used a general arithmetic test developed and used in research studies by Shalev et al. (2001) to assess DD in adults (revised version of Rubinsten & Henik, 2005; see http://dx.doi.org/10.1037/0894-4105.19.5.641.supp). This test included 20 simple problems and 32 complex problems of the four arithmetical operations on integers and eight problems on decimals (the problems with fractions were not included because of a large variance in our norms that did not enable us to distinguish typical from atypical math development, the reason for this large variance being that many adult participants had forgotten the rules for computing fractions). The simple problems included single-digit additions and multiplications (e.g., 8 + 9 = __; 7 × 6 = __), and simple subtractions and divisions (e.g.,11 – 9 = __; 16 / 4 = __). The complex problems were two- and three-digit operand problems presented vertically on a sheet of paper (e.g., 269 + 568 = __; 307 × 63 = __; 296 – 78 = __; 192 / 3 = __). The task did not have a time limit; total response latencies were recorded. The normative sample was created before the study and included 43 young adults (mean age: 20.07 ± 1.18) from the Université catholique de Louvain, who were in the same age window, spoke the same language, and were from the same cultural background and educational system. Finally, an arithmetic fluency task (*Tempo Test Rekenen*; de Vos, 1992) including five columns of simple arithmetic problems (one for each operation and one mixing the four operations) was used. Participants had 1 min per column to solve as many problems as possible. Each column started with easy single-digit problems and progressively increased in difficulty to end up with double-digit problems. The general arithmetic test and the fluency test are commonly used to select adults with DD (e.g., Attout & Majerus, 2015; Defever, Göbel, Ghesquière, & Reynvoet, 2014; Mejias, Grégoire, & Noël, 2012; Rubinsten & Henik, 2005).

To be included in the DD group, participants (a) had to have been diagnosed with DD by a speech therapist or a neuropsychologist or have complained of severe mathematical

Table 2. Performance in the Intelligence Test (*Advanced Progressive Matrices* test; Raven, Raven, & Court, 1998), in the General Arithmetic Test, and in the Subtests of the Arithmetic Fluency Test (TTR; de Vos, 1992) for Both the DD and Control Groups and Statistical Group Comparisons.

Variable	DD group *M* (*SD*)	Control group *M* (*SD*)	*t*(28)	*p* value
Reasoning score (Raven et al.)	21.5 (3.2)	23.7 (4.9)	−1.451	.158
General arithmetic test				
Number of errors	14.1 (5.5)	5.3 (3.7)	5.098	<.001
Total latency in seconds	1,049 (332)	782 (191)	2.704	.012
TTR				
Addition	29 (3)	34 (4)	−4.069	<.001
Subtraction	23 (4)	31 (3)	−5.421	<.001
Multiplication	21 (4)	29 (5)	−7.149	<.001
Division	16 (5)	29 (5)	−6.781	<.001
Mixed operation	20 (3)	30 (4)	−7.787	<.001

Note. Standard deviation shown in parentheses. TTR = *Tempo Test Rekenen*; DD = developmental dyscalculia.

difficulties since primary school, (b) had to present an IQ score as estimated by the *Advanced Progressive Matrices* test superior to −1 standard deviation compared to the standardized mean, and (c) had to perform below 1.5 standard deviations in the general arithmetic test in terms of latency or accuracy compared to the control group and/or to perform at or below the fifth-grade level on at least two subtests of the arithmetic fluency task (only norms for children are provided in this test). The cutoff for the arithmetic fluency task was chosen because in Wallonia (the French-speaking part of Belgium), all the multiplication tables have been taught/trained by the end of this grade, meaning that a score equal or below the level of the fifth grade would indicate a very poor arithmetic fact performance. Control participants were required to have had no complaints about mathematics and to have performed above −1 standard deviation in the general arithmetic test compared to the control group and above the fifth-grade level on at least four of the five subtests of the arithmetic fluency task. They also had to present an IQ score as estimated by the *Advanced Progressive Matrices* test superior to −1 standard deviation compared to the standardized mean.

The direct comparison of DD and control groups showed that they were similar in terms of intelligence (Table 2). As expected, the participants with DD performed worse than the control group in the general arithmetic test in terms of speed and accuracy and in the different parts of the arithmetic fluency test (Table 2).

Material, Tasks, and Stimuli

Stimuli presentation and data collection were controlled by a Dell laptop using a customized E-Prime program (Schneider, Eschman, & Zuccolotto, 2002). Four tasks were used in which the participants had to categorize (a) the numerosity of sequences of rapidly flashing dots (hereafter, Numerosity), (b) the duration of presentation of a single dot (hereafter, Duration), (c) the length of a black rectangle (hereafter, Length), and (d) the identity of faces (hereafter, Face). In the Numerosity task, the participants had to decide for each sequence whether it contained “few” or “many” dots by pressing a left- or right-hand response button (corresponding, respectively, to the letters *S* and *L* on the computer keyboard). The stimuli were sequences of five, six, eight, or nine black dots (diameter: 4° of visual angle) presented one at a time at the center of the computer screen. Sequences with five and six dots corresponded to the *few* category, while sequences with eight and nine dots corresponded to the *many* category (Figure 1). The sequences were constructed using nonperiodic signals such that temporal ratios did not constitute a potential confound, and rhythm biases were avoided (for more methodological details, see Breukelaar & Dalrymple-Alford, 1998; Dormal, Seron, & Pesenti, 2006). Specifically, for each trial, the temporal pattern for the numerosity-relevant signal was randomly generated by adjusting the duration of the events and the interevent intervals. The total duration of the sequences (i.e., the duration of the dots plus the interdot intervals) was kept constant (1,500 ms), whereas the duration of each dot and of the interdot intervals varied randomly from 50 to 270 ms. Moreover, each series involved at least one dot and one interdot interval of 50 ms and one longer than 200 ms, in order to avoid pattern recognition. In the Duration task, the participants categorized each dot as being presented for a “short” or a “long” duration. The stimuli were composed of a single black dot (diameter: 4° of visual angle) presented at the center of a 15.6-inch computer screen for 550, 600, 850, or 900 ms. To avoid potential explicit or implicit counting strategies, short durations (i.e., under 1 s) were used. The durations of 550 and 600 ms constituted the short intervals, whereas those of

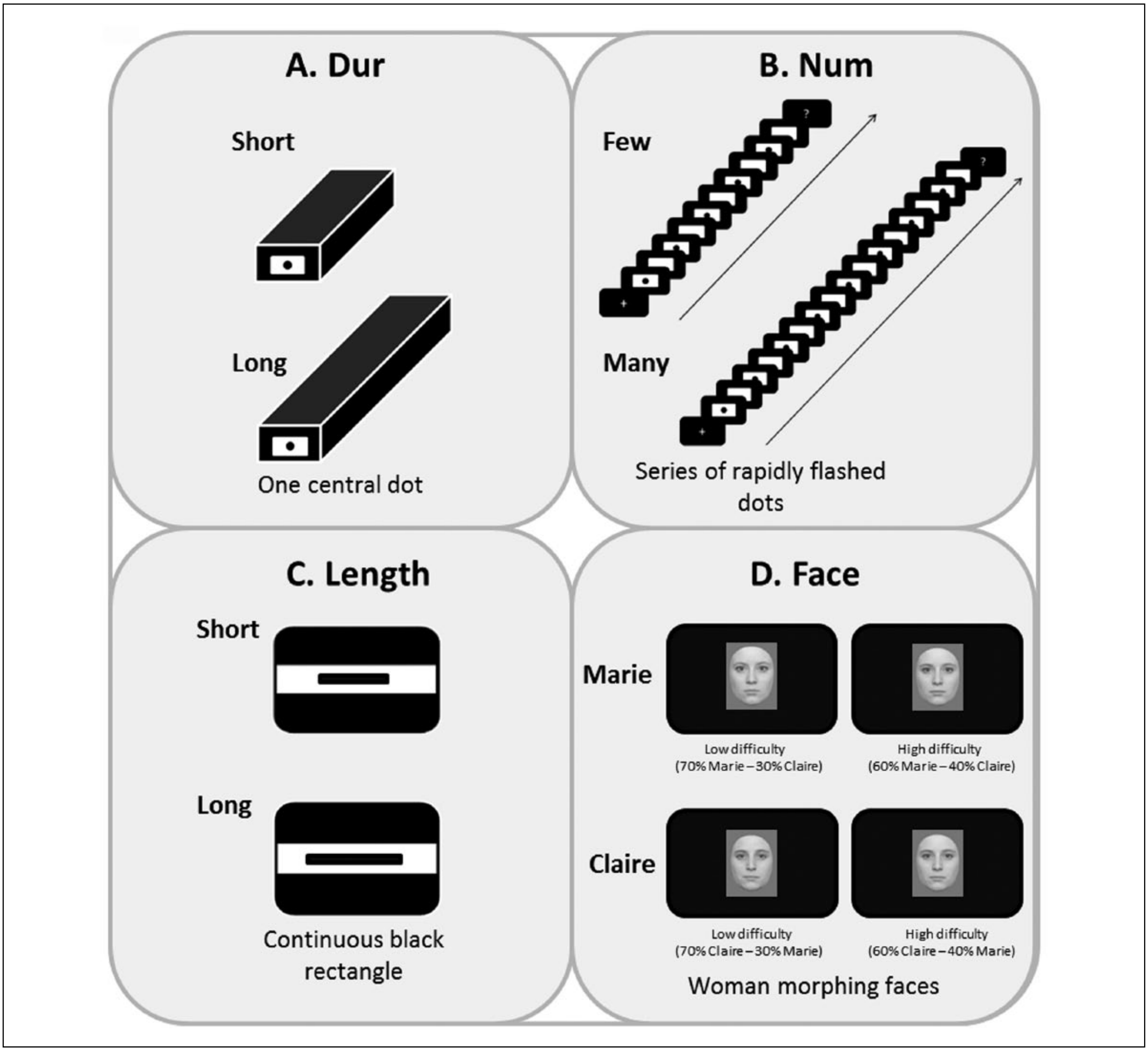

Figure 1. Example of stimuli of each category for the four categorization tasks. Participants had to decide (A) whether the dot stimulus was presented for a "short" (left-button response) or a "long" (right-button response) period (Duration task), (B) whether each sequence contained "few" or "many" dots (Numerosity task), (C) whether each horizontal rectangle was "short" or "long" (Length task) and (D) whether the presented face corresponded to "Marie" or "Claire" (Face task) with the same response buttons.

850 and 900 ms corresponded to the long ones. In the Length task, the participants had to decide whether a rectangle was "short" or "long" by using the same two-choice button presses. The stimuli were composed of one black rectangle of 8, 8.5, 9, or 9.5 cm length and 1 cm wide displayed at the center of the computer screen for 250 ms. Rectangles of 8 and 8.5 cm belonged to the *short* category, whereas rectangles of 9 and 9.5 cm belonged to the *long* one. Finally, in the Face task, the participants categorized each face as representing one person or another, with the same response keys as the other tasks. The stimuli were composed of a female face presented at the center of the screen for 250 ms. Four different faces were created by morphing two young female faces belonging to two people (fictitiously named Claire and Marie) using Morpheus Photo Morpher v3.17 software (Morpheus Development, LLC). There were two levels of difficulty: The low difficulty level corresponded to faces composed of 70% of one person and 30% of the other person (i.e., one being dominantly Claire, the other Marie), while the high difficulty level corresponded to faces composed of

60% of one person and 40% of the other or vice versa. The faces were presented in color, cropped off for external features, and displayed on a gray background at a size of 170 to 200 pixels of width and 250 pixels of height (about 5 cm wide and 7 cm high on the screen). Figure 1 shows an example from each category (i.e., short/long, few/many, or Marie/Claire) for each categorization task. The selection of the different stimuli of each category was based on the results of pilot studies for calibrating the different tasks so that they are sensitive (no ceiling or floor effect), are equivalent in terms of global response latencies and error rate, and show similar effect of distance/difficulty.

Procedure

The participants sat in a quiet room at a viewing distance of approximately 50 cm from the screen. Before the testing session, and for each categorization task, participants were trained to distinguish the various categories. The training consisted of a learning block and a training block with feedback. In the learning block, eight trials of each category were presented for the four tasks; participants were instructed to observe each trial carefully, but the duration of the presentation of single dots, the numerosity of the sequences, and the length of the rectangles were not mentioned. During the training block with feedback, eight trials from each category (short/long, few/many, or Claire/Marie) were presented in a randomized order within each task, and participants were required to categorize each sequence as containing few or many dots, each single dot as lasting a short or long period of time, each rectangle as being short or long, and each face as belonging to Claire or Marie by pressing a left- or right-hand response button on the keyboard. Visual feedback informed the participants after each trial of whether or not their answer was correct.

After the training, all participants took part in the testing session. Each participant performed two blocks of each task (Duration, Numerosity, Length, and Face), each block containing 32 trials (corresponding to 16 presentations of each category of items in total). The order of the experimental tasks was counterbalanced across participants.

Results

Possible differences in the level of difficulty across the tasks were measured in terms of the classical distance effect (Moyer & Landauer, 1967). Numerosities were classified as "easy" or "difficult": Easy numerosities corresponded to sequences of five and nine dots, which are respectively at the lower and upper extreme of the range and are thus easier to discriminate; difficult numerosities corresponded to sequences with six and eight dots. Following the same rationale, sequences lasting 500 and 900 ms or rectangles of 8 and 9.5 cm constituted the easy duration/length and sequences of 600 and 800 ms or rectangles of 8.5 and 9 cm the difficult duration/length. Finally, as mentioned above, morphing faces composed of 70% of one person and 30% of the other person corresponded to the easy faces, while the difficult faces corresponded to faces composed of 60% of one person and 40% of the other.

For each combination of task and difficulty, we computed the individual error rate (ER) and the median response latency of correct trials only (RL). These values were entered in separate analyses of variance (ANOVA) with group (DD vs. control) as a between-subject variable and task (Duration, Numerosity, Length vs. Face) and difficulty (easy vs. difficult) as within-subject variables. Post hoc comparisons were performed using two-tailed t tests, adjusted for multiple comparisons using Bonferroni correction (hereafter, BC) when necessary.

ER

A main effect of group, $F(1, 28) = 4.067$, $p = .05$, $\eta^2 = .127$, indicated that overall, the mean ER was higher in the DD group (15.67% ± 5.23%) than in the control group (11.67 ± 5.65 %). A main effect of task, $F(3, 84) = 13.677$, $p < .001$, $\eta^2 = .328$, was revealed: Fewer errors were made in the Length task (5.33% ± 4.25%) compared to the three other tasks (Numerosity, 13.02% ± 9.55%; Duration, 15.75% ± 11.36%; Face, 20.58% ± 13.32%; all p_{BC} values < .002), which did not differ between them (all p_{BC} values > .1). Moreover, a main effect of difficulty, $F(1, 28) = 168.557$, $p < .001$, $\eta^2 = .858$, showed that the difficult stimuli (19.25% ± 6.66%) were more error prone than the easy stimuli (8.10% ± 5.71%). An interaction between task and difficulty was also found, $F(3, 84) = 17.073$, $p < .001$, $\eta^2 = .379$. In each task, the ER of the difficult stimuli was significantly higher than the ER of the easy ones (all p_{BC} values < .001). No difference was observed between the difficult stimuli of Numerosity (19.55% ± 10.22%) and Duration (18.99% ± 12.79%), $t(29) = 0.233$, *ns*, while the easy stimuli of Numerosity (6.49 ± 11.66 %) differed significantly from the easy stimuli of Duration (12.51% ± 11.19%), $t(29) = 2.073$, $p_{BC} = .047$. More importantly, a significant interaction between task and group was observed, $F(3, 84) = 2.878$, $p = .041$, $\eta^2 = .093$. The two groups did not differ in the Length and Face tasks, $t(28) = 1.379$, $p_{BC} =.183$, and $t(28) = 0.636$, $p_{BC} =.53$, respectively, whereas in the Numerosity and Duration tasks, the DD group (Numerosity, 16.33% ± 11.24%; Duration, 20.95% ± 12.53%) performed worse compared to the control group (Numerosity, 9.72% ± 6.26%; Duration, 10.53% ± 7.24%), $t(28) = 1.99$, $p_{BC} = .05$, and $t(28) = 2.79$, $p_{BC} = .009$, respectively (Figure 2). No other interaction was found.

RLs

A similar ANOVA performed on the RLs revealed no main effect of group, $F(1, 28) = 0.752$, *ns*. There was a main effect of task, $F(3, 84) = 9.723$, $p < .001$, $\eta^2 = .258$, showing that the Length task (329 ± 168 ms) was performed globally faster than the Numerosity (461 ± 78 ms), $t(29) = 4.929$, $p_{BC} < .001$, and Duration tasks (423 ± 107 ms), $t(29) = 3.455$, $p_{BC} = .012$, whereas the Face task (383 ± 150 ms) was faster than the Numerosity task, $t(29) = 2.880$, $p_{BC} = .042$, only. There was also a main effect of difficulty, $F(1, 28) = 15.314$, $p = .001$, $\eta^2 = .354$, indicating that the easy stimuli (451 ± 102 ms) were processed faster than the difficult stimuli (473 ± 98 ms). A significant three-way interaction between task, difficulty and group, $F(3, 84) = 4.095$, $p = .009$, $\eta^2 = .128$, was observed. To decompose this interaction, we carried out separate ANOVAs for each task with difficulty as a within-subject variable and group as a between subject variable. In the Face and Length tasks, only a main effect of difficulty was observed, $F(1, 28) = 5.862$, $p = .022$, $\eta^2 = .173$; $F(1, 28) = 8.681$, $p = .006$, $\eta^2 = .237$, respectively, showing that the easy stimuli (Face, 360 ± 158 ms; Length, 321 ± 169 ms) were processed faster than the difficult ones (Face, 405 ± 157 ms; Length, 338 ± 168 ms); no main effect of group or interaction was present (all p_{BC} values > .1). In the Duration task, a main effect of group was observed, $F(1, 28) = 4.407$, $p = .045$, $\eta^2 = .136$): Participants in the DD group (462 ± 104 ms) were globally slower than controls (385 ± 100 ms); no main effect of difficulty or interaction was observed (all p_{BC} values > .7). Finally, in the Numerosity task, a significant main effect of difficulty, $F(1, 28) = 4.383$, $p = .045$, $\eta^2 = .135$, was observed and interacted with group, $F(1, 28) = 6.388$, $p = .017$, $\eta^2 = .186$ (Figure 3): While the easy stimuli (421 ± 61 ms) were processed faster than the difficult ones (477 ± 117 ms), $t(14) = 2.663$, $p_{BC} = .019$) in the control group, no significant difference, $t(14) = 0.437$, *ns*, was observed between the two levels of difficulty in the DD group (low, 474 ± 60 ms; high, 469 ± 87 ms). Moreover, a significant difference was observed between DD and control groups for the easy level only, $t(28) = 1.949$, $p_{BC} = .03$). No main effect of group or other interaction was observed (all p_{BC} values > .4).

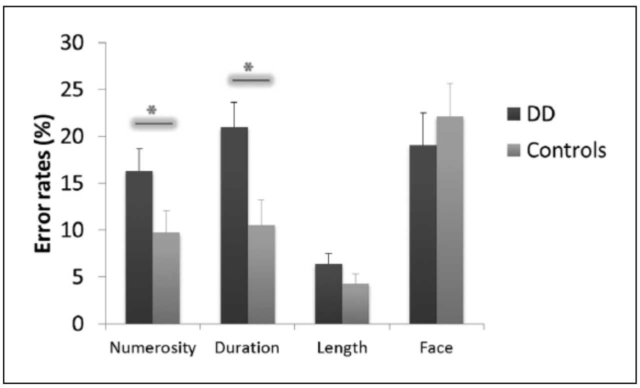

Figure 2. Mean error rate (± *SE*) as a function of task (Numerosity, Duration, Length vs. Face) and group (developmental dyscalculia vs. control). Asterisks indicate significant differences (*p* <.05).

Correlations

To test whether magnitude deficits are related to each other, bivariate Pearson's correlation between the performance in the Numerosity and the Duration tasks was computed since

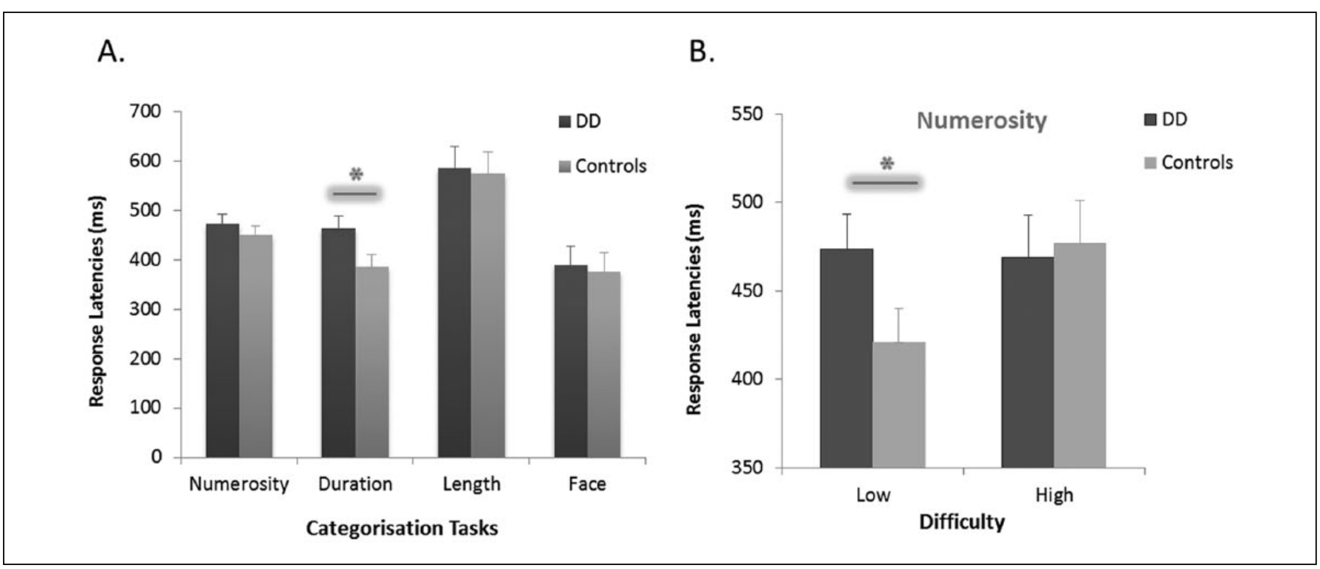

Figure 3. (A) Mean response latencies (± *SE*) as a function of task (Numerosity, Duration, Length vs. Face) and group (developmental dyscalculia vs. control). (B) Mean response latencies (± *SE*) for the Numerosity task as a function of difficulty (low vs. high) and group (developmental dyscalculia vs. control). Asterisks indicate significant differences (*p* < .05).

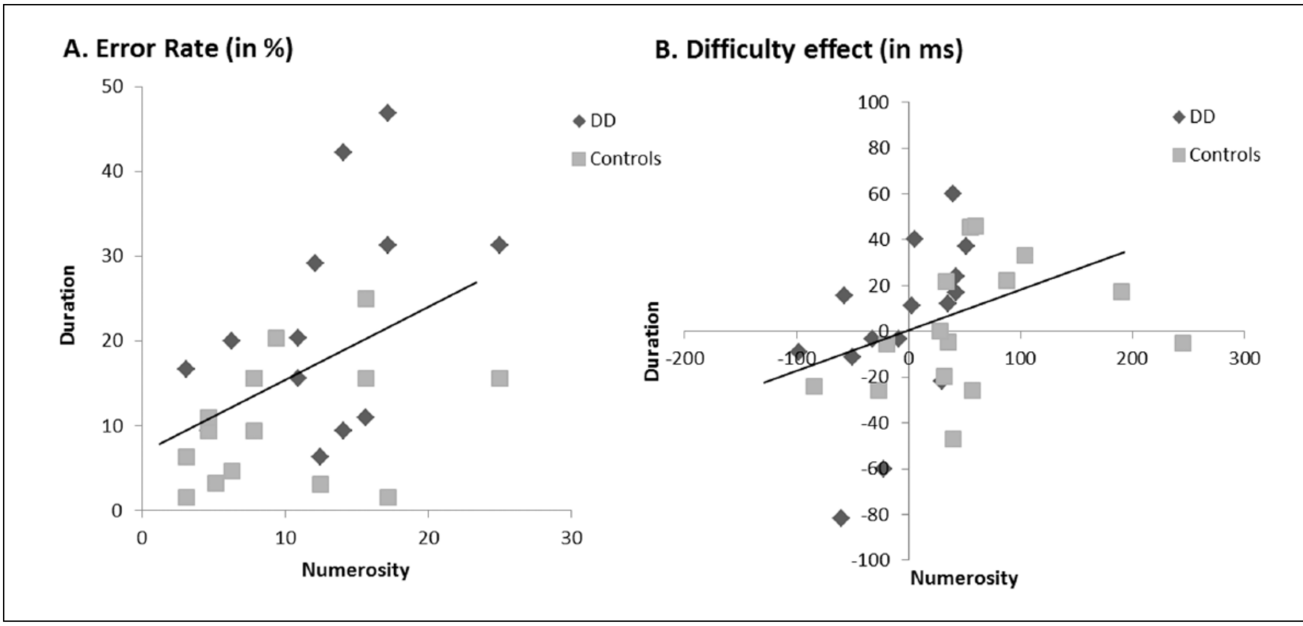

Figure 4. (A) Mean error rate (in %) and (B) mean response latencies' difficulty effect (in milliseconds) for each participant in the Numerosity and Duration tasks as a function of group (developmental dyscalculia vs. control).

participants in the DD group differed from the controls in both. For both the ER and the RLs' difficulty effect, moderate but significant partial correlations controlling for the group between the Numerosity and the Duration tasks, $r(25) = .389$, $p = .045$; $r(27) = .393$, $p = .035$, respectively, were observed (Figure 4). For the sake of completeness, we ran partial bivariate Pearson's correlations between the other magnitude tasks on the global ER and on the RLs' differences between easy and difficult levels. However, none of the correlations were significant (global ER: Numerosity–Length, $r(25) = .199$, $p = .320$; Duration–Length, $r(25) = .185$, $p = .357$; RLs difficulty: Numerosity–Length, $r(27) = .308$, $p = .104$; Duration–Length, $r(25) = .275$, $p = .149$).

We also investigated the link between the performance in the general arithmetic test (the ER and the total time separately) and the performance at the different magnitude tasks, using bivariate correlations. Only the global ER of Duration and the Numerosity RLs' differences between easy and difficult levels correlated with the ER in the general arithmetic test; respectively, $r(26) = .386$, $p = .043$; $r(28) = –.378$, $p = .039$; all other p values > .5. However, the same correlations controlling for group were not significant; respectively, partial $r(25) = .168$, $p = .401$; partial $r(27) = –.098$, $p = .614$. Correlations with the other magnitude tasks did not reach significance (all p values > .1).

Complementary Analyses

Since the Numerosity and Duration tasks are both sequential and require accumulating information over time, the above-presented findings might be explained by a working memory deficit in the DD group. Indeed, the accumulator model assumes that participants have to accumulate each unit of time or event; then, the pulses summed in the accumulator are stored for a short period in a working memory buffer before being compared to previously memorized numerical or temporal references (Meck & Church, 1983). The more pulses are accumulated, the more working memory is requested. In order to exclude the potential confound of working memory differences between the two groups, additional analyses were carried out with the following predictions. In the case of a working memory deficit in the DD group, higher memory load (corresponding to more numerous or longer stimuli) should increase the difference between groups compared to low memory load (corresponding to less numerous or shorter stimuli). We therefore ran a repeated-measures ANOVA including task (Numerosity vs. Duration) and memory load (low, five and six dots, 550 and 600 ms; vs. high, eight and nine dots, 850 and 900 ms) as within-subject variables and group (DD vs. controls) as a between-subject variable. Regarding the ER, an interaction between task and memory load was observed, $F(1, 28) = 9.748$, $p = .004$, $\eta^2 = .258$. Surprisingly, more errors were found for the stimuli with few dots (16.03% ± 13.72%) than with many dots (10.13% ± 11.05%) in the Numerosity task, $t(29) = 2.028$, $p = .052$. Contrariwise, more errors were found for the long durations (18.80% ± 15.07%) compared to short durations (12.70% ± 11.99%) in the Duration task, $t(29) = −2.230$, $p = .034$. As expected this analysis revealed a main effect of group, $F(1, 28) = 10.777$, $p = .003$: Adults with DD

(18.65% ± 8.30%) made more errors than the control group (10.18% ± 5.57%). No effect of task or memory load was found (all p values > .279). More importantly, no interaction between memory load and group or between task and group, nor the triple interaction, was found (all p values > .166). Regarding the RLs, the same ANOVA revealed a main effect of memory load, $F(1, 28) = 37.914$, $p < .001$, $\eta^2 = .575$: High memory load (418 ± 78 ms) took more time than low memory load (466 ± 83 ms). The DD group (467 ± 65 ms) tended to be slower than the control group (417 ± 83 ms), but this did not reach the significance threshold, $F(1, 28) = 3.450$, $p = .074$, $\eta^2 = .110$. Memory load interacted with task, $F(1, 28) = 8.577$, $p = .007$, $\eta^2 = .234$. No effect of memory load was found in the Numerosity task (low, 471 ± 16 ms; high, 451 ± 83 ms), $t(29) = 1.435$, $p = .162$, while high memory load (385 ± 105 ms) took more time than low memory load (462 ± 117 ms) in the Duration task, $t(29) = 6.930$, $p < .001$. Importantly, no interaction between memory load and group was found, $F(1, 28) = 3.433$, $p = .074$, $\eta^2 = .109$. More precisely, the DD group (499 ± 72 ms) tended to be slower than the control group (434 ± 82 ms) for the low memory load, $t(28) = 2.310$, $p = .028$, while no difference between groups was found in the high memory load (DD group, 436 ± 66 ms; control group, 400 ± 88 ms), $t(28) = 1.261$, $p = .218$. No interaction between task and group and no triple interaction was found (all p values > .15). Altogether, these analyses allowed us to dismiss the hypothesis that a possible working memory deficit in the DD group explained our findings, since no larger difference between groups was found in the high-memory-load condition compared to the low working memory load.

Discussion

This study aimed at determining whether the numerical deficit observed in adults with DD possibly extended to other aspects of non-numerical magnitude processing. To this end, the performance of adults with DD and age-matched controls was compared in numerosity, duration, and length categorization tasks.

First, our results show, as expected, that adults with DD have problems in performing the numerosity categorization task correctly. Indeed, their global accuracy in this task was significantly lower than that of the control participants. Moreover, adults with DD did not show any speed advantage when processing "easy" items, while controls did, as demonstrated by the absence of a difficulty effect on the response latencies. Previous studies exploring numerosity processing with simultaneously presented materials (i.e., collection of dots) reported a numerical deficit in both children (Mazzocco, Feigenson, & Halberda, 2011; Mussolin et al., 2010; Piazza et al., 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007) and adults (Gilaie-Dotan et al., 2014). Our results corroborate these findings and extend them to a sequential mode of presentation (i.e., sequences of flashing dots), allowing the exclusion of all visuospatial confounds and suggesting the presence of a mode-independent impairment of nonsymbolic numerical magnitude in DD (Butterworth, 2010; Piazza et al., 2010).

Second, an impairment in the duration categorization task was also observed: Adults with DD were slower and less accurate than controls. Our findings extend previous studies (Skagerlund & Träff, 2014; Vicario et al., 2012) that reported a deficit of discrimination of durations in children with DD. Our study reveals a duration processing deficit (subsecond intervals) in adults with DD, indicating that a duration processing deficit is present in people with a persistent math deficit. Importantly, our design did not include numbers in the Duration task, excluding the alternative explanation in terms of number symbol deficit. The presence of correlations between the performance (in terms of both ER and difficulty effect) in the Numerosity and Duration tasks fully supports the idea of a partly shared representation or processing system, as initially formulated by Meck and Church (1983) and extended by Walsh (2003) in his ATOM model. This common system has been supposed to work as an accumulator estimating duration and numerical quantities. The idea of this model is that a pacemaker transmits pulses to an accumulator via a mode-switch system. This mode-switch system can estimate duration by a run or stop mode that accumulates the number of pulses emitted during a given period of time. For the processing of numerical quantities, the same system operates as a counter when it is on an event mode. On the basis of their seminal experiments with rats, Meck and Church proposed that this pacemaker is used for the discrimination of both dimensions. According to our findings, this system could therefore be impaired in adults with DD.

Finally, although visuospatial difficulties have often been reported in the population with DD (e.g., Ansari & Karmiloff-Smith, 2002; Skagerlund & Träff, 2014), the perception of length per se did not appear impaired in our adults with DD. Indeed, no significant difference was observed compared to the control group in terms of both speed and accuracy. These results are in line with previous studies showing a preserved representation of space itself (Cappelletti et al., 2014; Huber, Sury, Moeller, Rubinstein, & Nuerk, 2015; Mussolin et al., 2011) and postulating that it may be a visuospatial memory deficit that is at the origin of spatial difficulties observed in other tasks (Huber et al., 2015; Skagerlund & Träff, 2014; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). However, it is worth noting that the global level of difficulty of the Length task appeared to be slightly lower compared to the Numerosity and Duration tasks, as indicated by globally faster RLs and lower ERs. Therefore, the absence of deficit for this task in adults with DD has to be interpreted cautiously, and future studies using more elaborate spatial tasks should help in clarifying this issue.

Altogether, the presence of both impaired (i.e., numerosity and duration) and preserved (i.e., length) magnitude processes in adults with DD did not support the existence of a fully shared magnitude processing system. The numerical and temporal difficulties observed could therefore not be explained by a general deficit to a magnitude representation system. Our findings support the view that both common and partially independent mechanisms and/or representations for magnitudes coexist within the brain (Cappelletti, Freeman, & Cipolotti, 2011; Dormal et al., 2012; Van Opstal & Verguts, 2013; Walsh, 2003). The exact nature of the common and specific mechanisms involved in magnitude processing is, however, not fully understood. Some authors proposed that magnitudes are processed separately but interact at later decisional or motor stages (e.g., Cohen Kadosh, Lammertyn, & Izard, 2008; Huntley-Fenner, Carey, & Solimando, 2002; McCrink & Wynn, 2004) or in working memory (e.g., Van Dijck & Fias, 2011; Van Opstal & Verguts, 2013). This common deficit cannot be interpreted as a decision-making or an episodic memory deficit, since adults with DD performed similarly to controls in the control face categorization task. But the joint numerical and temporal deficit observed in our DD sample cannot be explained by a decisional, an episodic memory, or a motor response problem, since adults with DD were able to correctly perform the two other categorization tasks (i.e., length and face) that were matched for these aspects. Moreover, although working memory is certainly involved in our categorization tasks and could potentially explain DD difficulties, complementary analyses showed that our findings cannot be interpreted by a unique deficit in working memory. Indeed, if a working memory deficit in the DD group underlined our findings, larger differences between groups in high-memory-load conditions (i.e., many dots or long durations) than in low-memory-load conditions (i.e., few dots or short durations) should have been observed. However, no interaction between memory load and group was found in the Numerosity or the Duration task in terms of ERs as well as RLs. Future studies in which the tasks would include a direct manipulation of the working memory load are needed to firmly conclude that working memory does not explain the link between numerosity and duration processing. However, all the elements reported here do not support the view that working memory accounts for our results.

By testing adults with DD, our study shows that very basic magnitude processing is impaired in people who can reliably be diagnosed with DD since they show a persistent deficit that has not been reduced through development, education, and/or treatment. While longitudinal studies track the trajectories of learning and processing, studying adults enabled us to evaluate long-term deficit(s). In the present study, the aim was to explore the integrity of processing of three different magnitudes in adults with DD, and for that purpose, we chose to run a group study as a first investigation. However, the heterogeneity of dyscalculia has been pointed out by many researchers (see, for instance, Rubinsten & Henik, 2009; Wilson & Dehaene, 2007). The group effect shows that numerosity and duration processing are impaired in at least several adults with DD but does not mean that this deficit is present in all individuals with DD. Future studies should investigate the different profiles of impairment that can be found and the link between, on one hand, duration and numerical processing deficit and, on the other hand, the different components of mathematics.

To sum up, our study reports a deficit of numerosity and duration processing in adults with DD and no evidence of a length-processing deficit. These findings suggest that DD is characterized by a nonsymbolic magnitude deficit that is not restricted to numerosity processing but extends to duration processing. This double deficit possibly reflects the impairment of an accumulator system that has been suggested as a common element in numerosity and duration processing (Meck & Church, 1983). Accordingly, beyond numerosity processing, future studies should investigate the processing of duration in the diagnosis and treatment of DD and better understand its relationship with math ability. If numerosity and duration processing share a common mechanism, one could imagine that training one of the dimensions could enhance the other and might improve global math ability. Our findings should also be implemented within the models of heterogeneity of DD and contribute to distinguishing the different profiles of DD.

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References

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

Ansari, D., & Karmiloff-Smith, A. (2002). Atypical trajectories of number development: A neuroconstructivist perspective. *Trends in Cognitive Sciences*, *6*(12), 511–516. doi:10.1016/S1364-6613(02)02040-5

Ashkenazi, S., & Henik, A. (2010). A disassociation between physical and mental number bisection in developmental dyscalculia. *Neuropsychologia*, *48*(10), 2861–2868. doi:10.1016/j.neuropsychologia.2010.05.028

Attout, L., & Majerus, S. (2015). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology*, *21*(4), 432–450. doi:10.1080/09297049.2014.922170

Brannon, E. M., & Roitman, J. D. (2003). Nonverbal representations of time and number in animals and human infants. In W. H. Meck (Ed.), *Functional and neural mechanisms of interval timing* (pp. 143–182). Boca Raton, FL: CRC Press. doi:10.1201/9780203009574.ch6

Breukelaar, J. W., & Dalrymple-Alford, J. C. (1998). Timing ability and numerical competence in rats. *Journal of Experimental Psychology. Animal Behavior Processes*, *24*, 84–97. doi:10.1037/0097-7403.24.1.84

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *364*(1525), 1831–1840. doi:10.1098/rstb.2009.0028

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry*, *46*, 3–18. doi:10.1111/j.1469-7610.2005.00374.x

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences*, *14*(12), 534–541. doi:10.1016/j.tics.2010.09.007

Cappelletti, M., Chamberlain, R., Freeman, E. D., Kanai, R., Butterworth, B., Price, C. J., & Rees, G. (2013). Commonalities for numerical and continuous quantity skills at temporo-parietal junction. *Journal of Cognitive Neuroscience*, *26*(5), 986–999. doi:10.1162/jocn_a_00546

Cappelletti, M., Freeman, E. D., & Butterworth, B. L. (2011). Time processing in dyscalculia. *Frontiers in Psychology*, *2*, 364. doi:10.3389/fpsyg.2011.00364

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2009). Dissociations and interactions between time, numerosity and space processing. *Neuropsychologia*, *47*(13), 2732–2748. doi:10.1016/j.neuropsychologia.2009.05.024

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2011). Numbers and time doubly dissociate. *Neuropsychologia*, *49*(11), 3078–3092. doi:10.1016/j.neuropsychologia.2011.07.014

Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology*, *84*, 132–147. doi:10.1016/j.pneurobio.2007.11.001

Cohen Kadosh, R., & Walsh, V. (2009). Numerical representation in the parietal lobes: Abstract or not abstract? *Behavioral and Brain Sciences*, *32*(3/4), 313–328. doi:10.1017/S0140525X09990938

Defever, E., Göbel, S. M., Ghesquière, P., & Reynvoet, B. (2014). Automatic number priming effects in adults with and without mathematical learning disabilities. *Frontiers in Psychology*, *5*, 4. doi:10.3389/fpsyg.2014.00004

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384–398. doi:10.1016/j.neuron.2007.10.004

De Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 4809–4813. doi:10.1073/pnas.1323628111

De Smedt, B., & Gilmore, C. K. (2011). Defective number module or impaired access? 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

De Smedt, B., Noël, M. P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education*, *2*, 48–55. doi:10.1016/j.tine.2013.06.001

De Vos, T. (1992). *TTR Tempo-Test-Rekenen*. Sint-Niklaas, Belgium: Swets and Zeitlinger.

Dormal, V., Andres, M., & Pesenti, M. (2008). Dissociation of numerosity and duration processing in the left intraparietal sulcus: a transcranial magnetic stimulation study. *Cortex*, *44*(4), 462–469. doi:10.1016/j.cortex.2007.08.011

Dormal, V., Dormal, G., Joassin, F., & Pesenti, M. (2012). A common right fronto-parietal network for numerosity and duration processing: an fMRI study. *Human Brain Mapping*, *33*(6), 1490–1501. doi:10.1002/hbm.21300

Dormal, V., Grade, S., Mormont, E., & Pesenti, M. (2012). Dissociation between numerosity and duration processing in aging and early Parkinson's disease. *Neuropsychologia*, *50*(9), 2365–2370. doi:10.1016/j.neuropsychologia.2012.06.006

Dormal, V., & Pesenti, M. (2009). Common and specific contributions of the intraparietal sulci to numerosity and length processing. *Human Brain Mapping*, *30*(8), 2466–2476. doi:10.1002/hbm.20677

Dormal, V., & Pesenti, M. (2012). Processing magnitudes within the parietal cortex. In A. Costa, & E. Villalba (Eds.), *Horizons in Neuroscience Research* (Vol. 8, pp. 107–140). New York: Nova Science Publishers.

Dormal, V., Seron, X., & Pesenti, M. (2006). Numerosity-duration interference: a Stroop experiment. *Acta Psychologica*, *121*(2), 109–124. doi:10.1016/j.actpsy.2005.06.003

Gallistel, C. R., & Gelman, R. (2000). Non-verbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences*, *4*(2), 59–65. doi:10.1016/S1364-6613(99)01424-2

Gebuis, T., & Reynvoet, B. (2012). The interplay between non-symbolic number and its continuous visual properties. *Journal of Experimental Psychology. General*, *141*(4), 642–648. doi:10.1037/a0026218

Gilaie-Dotan, S., Rees, G., Butterworth, B., & Cappelletti M. (2014). Impaired numerical ability affects supra-second time perception. *Timing and Time Perception, 2*(2), 169–187. Retrieved from http://dx.doi.org/10.1163/22134468-00002026

Hayashi, M. J., Kanai, R., Tanabe, H. C., Yoshida, Y., Carlson, S., Walsh, V., & Sadato, N. (2013). Interaction of numerosity and time in prefrontal and parietal cortex. *Journal of Neuroscience*, *33*(3), 883–893. doi:10.1523/JNEUROSCI.6257-11.2013

Huber, S., Sury, D., Moeller, K., Rubinsten, O., & Nuerk, H. C. (2015). A general number-to-space mapping deficit in developmental dyscalculia. *Research in developmental disabilities, 43*, 32–42.

Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: Perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition*, *85*, 203–221.

Hurewitz, F., Gelman, R., & Schnitzer, B. (2006). Sometimes area counts more than number. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 19599–19604. doi:10.1073/pnas.0609485103

Hurks, P. P. M., & Loosbroek, E. Van. (2012). Time estimation deficits in childhood mathematics difficulties. *Journal of Learning Disabilities*, *47*(5), 450–461. doi:10.1177/0022219412468161

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

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

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, *21*(6), 873–881. doi:10.1177/0956797610370158

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*(4), 1224–1237. doi:10.1111/j.1467-8624.2011.01608.x

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science*, *15*, 776–781.

Meck, W. H., & Church, R. M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology, Animal Behavior Processes*, *9*, 320–334. doi:10.1037/0097-7403.9.3.320

Mejias, S., Grégoire, J., & Noël, M.-P. (2012). Numerical estimation in adults with and without developmental dyscalculia. *Learning and Individual Differences*, *22*(1), 164–170. doi:10.1016/j.lindif.2011.09.013

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

Mussolin, C., Martin, R., & Schiltz, C. (2011). Relationships between number and space processing in adults with and without dyscalculia. *Acta Psychologica*, *138*(1), 193–203. doi:10.1016/j.actpsy.2011.06.004

Mussolin, C., Mejias, S., & Noël, M.-P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition*, *115*(1), 10–25. doi:10.1016/j.cognition.2009.10.006

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*, 65. doi:10.3389/fnhum.2011.00165

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*(1), 33–41. doi:10.1016/j.cognition.2010.03.012

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology: CB*, *17*(24), R1042–R1043. doi:10.1016/j.cub.2007.10.013

Raven, J., Raven, J. C., & Court, J. H. (1998). *Manual for Raven's Progressive Matrices and Vocabulary Scales: Section 4. The Advanced Progressive Matrices*. Oxford: UK: Oxford Psychologists Press.

Rousselle, L., Dembour, G., & Noël, M.-P. (2013). Magnitude representations in Williams syndrome: Differential acuity in time, space and number processing. *PLoS One*, *8*(8), e72621. doi:10.1371/journal.pone.0072621

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. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. *Neuropsychology*, *19*(5), 641–648. doi:10.1037/0894-4105.19.5.641

Rubinsten, O., & Henik, A. (2009). Developmental dyscalculia: Heterogeneity might not mean different mechanisms. *Trends in Cognitive Sciences, 13*(2), 92–99.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). E-Prime reference guide. *Psychology Software Tools*, *3*, 1. doi:10.1186/1756-0381-3-1

Shalev, R. S., Manor, O., Kerem, B., Ayali, M., Badichi, N., Friedlander, Y., & Gross-Tsur, V. (2001). Developmental dyscalculia is a familial learning disability. *Journal of Learning Disabilities*, *34*(1), 59–65.

Skagerlund, K., & Träff, U. (2014). Development of magnitude processing in children with developmental dyscalculia: space, time, and number. *Frontiers in Psychology*, *5*, 675. doi:10.3389/fpsyg.2014.00675

Szucs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex, 49*(10), 2674–2688.

Teghtsoonian, R., & Teghtsoonian, M. (1978). Range and regression effects in magnitude scaling. *Perception & Psychophysics, 24*, 305–314. doi:10.3758/BF03204247

Tudusciuc, O., & Nieder, A. (2009). Contributions of primate prefrontal and posterior parietal cortices to length and numerosity representation. *Journal of Neurophysiology*, *101*, 2984–2994. doi:10.1152/jn.90713.2008

Van Dijck, J.-P., & Fias, W. (2011). A working memory account for spatial-numerical associations. *Cognition*, *119*, 114–119. doi:10.1016/j.cognition.2010.12.013

Van Opstal, F., & Verguts, T. (2013). Is there a generalized magnitude system in the brain? Behavioral, neuroimaging, and computational evidence. *Frontiers in Psychology*, *4*, 435. doi:10.3389/fpsyg.2013.00435

Vicario, C. M., Rappo, G., Pepi, A., Pavan, A., & Martino, D. (2012). Temporal abnormalities in children with developmental dyscalculia. *Developmental Neuropsychology*, *37*(7), 636–652. doi:10.1080/87565641.2012.702827

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483–488.

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. *Human Behavior, Learning, and the Developing Brain: Atypical Development, 2*, 212–237.

Wynn, K. (1998). Psychological foundations of number: Numerical competence in human infants. *Trends in Cognitive Sciences*, *2*(8), 296–303. doi:10.1016/S1364-6613(98)01203-0